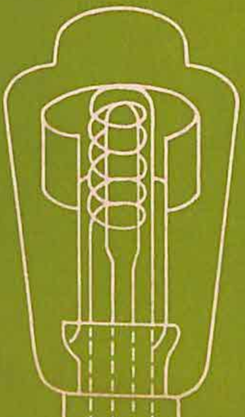
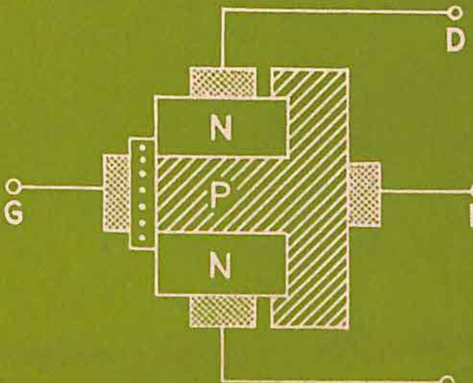
FUNDAMENTALS OF ELECTRONICS

A. B. Bhattacharya





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FUNDAMENTALS
OF
ELECTRONICS

[for Science & Engineering Degree Students]

BY

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Dedicated to
My Beloved
Parents

PREFACE

For many years I have felt that a working familiarity with fundamental aspects of electronics contributes immeasurably to all corners of scientific and engineering careers. Accordingly, this text is devoted to a discussion of basic physical concepts of Electronics and Radiophysics suitable for the undergraduate science (both Hons. and Pass) or engineering students (telecommunication or electrical with electronics special) and also partly for the students of post graduate classes of all Indian Universities.

Throughout the book I have, in my own teaching experience, attempted to keep the basic ideas in the forefront besides all mathematical complexity. The book is thus intended to provide a basic skeleton of some electronic devices and circuits to appreciate the operations and characteristics of many electronic instruments most likely to be useful to the students in their future works. Considerable emphasis has, therefore, been given to the illustrative examples worked out in the text and also to the review questions including problems and self-tests for a meaningful understanding of the subject matter instead of a casual hearsay acquaintance with it.

I am deeply indebted to Prof. M. K. Das Gupta of the Institute of Radiophysics and Electronics, Calcutta University and to Prof. D. L. Bhattacharya of the Department of Physics, Calcutta University for their kind suggestions and to many of my colleagues specially to Prof. S. B. Bhattacharya, Head of the Department of Physics, Serampore College for helpful discussions. Acknowledgements are due to Dr. S. K. Sarkar, Department of Physics, Calcutta University and to Dr. A. K. Sen, Centre of Advanced Study in Radio Physics and Electronics, Calcutta University for providing valuable criticisms. I must also express my sincere thanks to Sri Jamini Kanta Sen, Proprietor, Central Book Publishers for expediting the publication of the book. Finally, I like to mention the name of my wife, Mrs. Rina Bhattacharya, M.Sc., without whose devotion and encouragement this book could never have been completed.

The *Rasa Purnima* AUTHOR
11 November, 1981

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FOREWORD

To-day, it can be very rightly said that we live in the 'Age of Electronics'. In every branch of human endeavours, in every discipline of science and technology, the art and science of electronics play indeed a very vital role. The phenomenal developments in the fields of nuclear energy, space exploration, communication, instrumentation, control, computation and the like would not have been possible without the simultaneous progressive developments in this comparatively new branch of Science and Technology—Electronics. We saw the growth of the revolutionary developments in electronic devices, circuits and systems since the days of Hertz, Marconi, Bose, Lodge and Popov in the closing years of the last century. The two great World Wars accelerated the pace and scope of developments immensely. With the advent of large scale integrated circuits, microprocessors and opto-electronic devices it is indeed very hard to foresee the shape of things to come in the near future.

It is in the fitness of things that the 'Fundamentals of Electronics' have been introduced in the various levels of our curriculum. A significant portion on Electronics has been introduced in the Pass and Honours Physics course of our Universities besides the existing Post-graduate and Engineering degree courses. As always happens in a newly evolved discipline, dearth of good text books at a moderate price is being badly felt. Dr. A. B. Bhattacharya's bold attempt to bring out a text book entitled, 'Fundamentals of Electronics', will no doubt be praiseworthy. With the limited scope he has tried to develop the subject keeping in view the needs of our college students. I have had the opportunity of going through the contents of the book and of scanning through a couple of chapters. In my opinion, Dr. Bhattacharya's book will be well appreciated by all. Any new book can ultimately come to a stage of perfection if and only if the author gets constructive criticisms from both the teachers and the taught, which I hope will encourage Dr. Bhattacharya in due course.

I congratulate him for this venture and wish him success.

M K Das Gupta

(M. K. DAS GUPTA)

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FUNDAMENTALS OF ELECTRONICS

CHAPTER I

EMISSION OF ELECTRONS

1.1 Definition

The science of electronics is primarily concerned with the theory and application of devices which control current. Among these vacuum tubes and semiconductor devices are included. The diode introduced by Fleming in 1904, consisted of two metal electrodes, anode and cathode, may be taken as the first electronic device.

1.2 Concept of Electrons

It was Dalton (1802) who first gave an idea that all matters could be broken down into elements the tiniest particles of which were called atoms. According to Bohr's theory, an atom has a central nucleus of positive charge around which tiny negatively charged particles called electrons revolve in stationary orbits, just as the planets revolve round the sun. The nucleus of the atom is, in fact, made up of two fundamental particles, known as proton and neutron.

Out of the various elementary particles, electron is the most fundamental one. Its values of charge, mass and radius are given below:

Electronic charge $(Q_e) = 1.60210 \times 10^{-19}$ coulomb
$= 4.80298 \times 10^{-10}$ e.s.u.

Electronic rest mass $(m_e) = 9.1091 \times 10^{-31}$ kilogram
$= 5.48597 \times 10^{-4}$ a.m.u.

Electronic radius $(r_e) = 2.81777 \times 10^{-15}$ metres

Proton has a positive charge, magnitude equal to Q_e and mass 1837 m_e. Neutron has no charge but mass equal to 1837 m_e. There exist many other charged particles such as positron, etc. But due to high ratio of the charge to mass of an electron the motion of electron has become so useful in the field of electronic devices.

Electrons dislodged from the outer shell of an atom are called free electrons. Free electrons carry the current in all types of electron tubes and also in ordinary conductors. The movement of free electrons in antenna gives rise to electromagnetic radiations. Free electrons are thus responsible in most electrical and electronic phenomena.

1.3 Electron Emission

Electrons perform a certain amount of work to escape from the surface of emitter. To do this work energy is imparted to them from some external sources such as heat energy, kinetic energy of electric charges, energy stored in electric or magnetic fields and the light energy. Accordingly, the emission of electrons from a metallic surface is classified as follows:

(i) *Thermoionic (Primary) emission*: If electrons are emitted from a metal by supplying thermal energy, the process is called thermoionic emission. The number of electrons released depends on temperature. At a given temperature the thermoionic emission current density is obtained by an equation known as Richardson's law.

(ii) *Secondary emission*: When electrons at a high speed suddenly strike a metallic surface, some will collide directly with free electrons on the metal surface and project them outward. The electrons freed in this manner are called secondary emission.

(iii) *Field emission*: The presence of strong electric field set up by a high positive voltage outside the emitter surface may cause electron emission from it. The stronger the field applied, the greater will be the field emission from the cold emitter surface.

(iv) *Photoelectric emission*: In this process light energy called 'quanta' falling upon the emitter is transferred to the free electrons within the metal and speeds them up sufficiently to eject from the surface. The number of electrons emission will depend on the intensity of the beam falling upon the metallic surface.

Out of the four methods of emission discussed above, the thermoionic emission is the most vital one and most commonly used in electron tubes.

1.4 Richardson's Equation

A detailed mathematical explanation of the phenomenon of thermoionic emission was first successfully given by O. W. Richardson. He and later on Dushman applied the principles of Thermodynamics and Quantum Mechanics to establish the relation between the emission current density and temperature of the metal.

According to classical mechanics, if the electrons are considered as monatomic gas molecules then the average energy per degree of freedom of motion of an electron will be $\frac{1}{2} kT$, where k is the Boltzmann constant and T the absolute temperature. Now, if n be the number of free electrons in unit volume of the metal and dn the number having a velocity component normal to the surface lying within u and $u+du$ then by Maxwell's distribution law,

$$dn=n\sqrt{\frac{hm_e}{\pi}}\ \varepsilon^{-hm_e u^2}.\,du \qquad \ldots \qquad (1.1)$$

where, $h=\dfrac{1}{2kT}$

and m_e=mass of electron.

Richardson assumed that in order to escape from the surface layer, an electron has to do some work which can be denoted by $\phi\, Q_e$, where ϕ is the potential difference due to this work and Q_e is the charge of the electron. Correspondingly, the minimum kinetic energy required to just escape from the surface is given by,

$$\tfrac{1}{2}\, m_e\, u_0^2=\phi Q_e \qquad \ldots \qquad (1.2)$$

where u_o is the minimum velocity required in the direction concerned. The total number of electrons which strike the surface layer per unit area per second is $\int_0^\infty u\, dn$ out of which the number $\int_{u_o}^\infty u\, dn$ will be able to escape from the surface. The thermoionic current density, which is equal to the number of electrons that escape from the surface multiplied by the electronic charge Q_e, is therefore given by,

$$J=Q_e\int_{u_o}^{\infty} u\, dn$$

$$=n\, Q_e\sqrt{\frac{h\, m_e}{\pi}}\int_{u_o}^{\infty} \varepsilon^{-hm_e u^2}.\, u\, du$$

$$\because \quad d\left(\varepsilon^{-hm_e u^2}\right)=\varepsilon^{-hm_e u^2}\times\left(-hm_e 2u\right) du$$

$$\therefore \quad \varepsilon^{-hm_e u^2}\, u\, du=-\frac{1}{2hm_e}\, d\left(\varepsilon^{-hm_e u^2}\right)$$

Hence, $$J=-nQ_e\sqrt{\frac{hm_e}{\pi}}\cdot\frac{1}{2hm_e}\int_{u_0}^{\infty} d\left(\varepsilon^{-hm_e u^2}\right)$$

$$=\frac{nQ_e}{2}\sqrt{\frac{1}{hm_e\pi}}\,\varepsilon^{-hm_e u_0^2}$$

$$=\frac{nQ_e}{2}\sqrt{\frac{2kT}{m_e\pi}}\,\varepsilon^{-\frac{m_e u_0^2}{2kT}}$$

$$=nQ_e\sqrt{\frac{kT}{2m_e\pi}}\,\varepsilon^{-\frac{\phi Q_e}{kT}} \qquad \text{[using equation (1.2)]}$$

or $$J=AT^{1/2}\varepsilon^{-b/T} \qquad \ldots \qquad (1.3)$$

where $A=nQ_e\sqrt{\frac{k}{2m_e\pi}}$ and $b=\frac{\phi Q_e}{k}$

The equation (1.3) gives saturation current density which increases with the increase of temperature. The theoretical formula, however, agrees well with experimental results when $T^{1/2}$ is to be replaced by T^2. The modified expression was also later obtained by Richardson from thermodynamical considerations as discussed below.

Let us imagine a conductor with an emitting surface, constituting a wall of vacuum enclosure, at the other side of which a piston is fixed. For the electron gas outside the metal the pressure p can be expressed as,

$$p=\frac{RT}{V}=\frac{NkT}{V}=nkT \qquad \ldots \qquad (1.4)$$

where, n=number of electrons per unit volume.

If the piston is now isothermally raised so that the volume increases by dv then the work done by the electron gas due to isothermal expansion is $pdv=nkT\,dv$. Again if ϕ is the work function, which is the energy required by an electron to emit from the metal surface into the space, then the energy required for emission of ndv electrons into the increased space is $\phi n\,dv$. In Fig. 1.1 the isothermal expansion at T^o Kelvin is represented by PQ.

The piston is now drawing out to increase the volume adiabatically when the temperature falls to $(T-dT)$. This adiabatic expansion is given by QR in the figure. The emitter is next put in contact with a sink at a temperature $(T-dT)$ so that the electron gas is compressed isothermally to S wherefrom by an adiabatic compression SP the initial state is reached again.

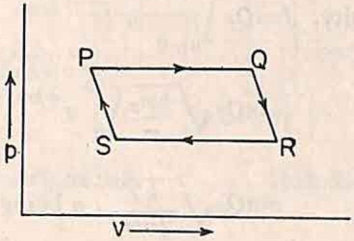

Fig. 1.1

Therefore, the work done by an electron gas in the reversible cycle$=[p-(p-dp)]dv=dp\ dv$ and the energy drawn from the source $=nkT\ dv+\phi n\ dv$. Now from the second law of thermodynamics, we have,

$$\frac{dp\ dv}{nkT\ dv+\phi n\ dv}=\frac{dT}{T}$$

or,
$$\frac{dp}{nkT+\phi n}=\frac{dT}{T} \qquad \dots \qquad (1.5)$$

Since, $dp=d(nkT)=kTdn+nk\,dT$

We have from equation (1.5),

$$\frac{kT\ dn+nk\ dT}{nkT+\phi n}=\frac{dT}{T}$$

or,
$$kT^2dn+nkT\ dT=nkT\ dT+\phi n\ dT$$

or,
$$\frac{dn}{n}=\frac{\phi dT}{kT^2} \qquad \dots \qquad (1.6)$$

If the energy required by an electron to emit from a surface at 0° Kelvin is ϕ_o then the energy required by it at T^o Kelvin will be

$$\phi_o+\tfrac{3}{2}kT,$$

since the thermal energy of a monatomic molecule at a temperature T^o is $\frac{3}{2}kT$. Hence we can replace ϕ in equation (1.6) by $\phi_o+\frac{3}{2}kT$.

i.e.
$$\frac{dn}{n}=\frac{\phi_o}{kT^2}dT+\frac{3}{2}\frac{dT}{T}$$

Integrating, $\log n = -\frac{\phi_o}{kT} + \frac{3}{2} \log T + \log a$ (a=constant of integration)

$$\therefore \qquad n = aT^{3/2}\, \varepsilon^{-\frac{\phi_o}{kT}}$$

So current density, $J = Qe \int_{u=0}^{u=\infty} u\, dn$

$$= nQe\sqrt{\frac{hm_e}{\pi}} \int_0^{\infty} \varepsilon^{-hm_e u^2}\, u\, du$$

$= nQe\sqrt{\frac{kT}{2\pi m_e}}$, u being the velocity of electron perpendicular to emitting surface.

Hence $J = Q_e\sqrt{\frac{kT}{2\pi m_e}}\, a\, T^{3/2}\, \varepsilon^{-\frac{\phi_o}{kT}}$ (substituting the value of n)

$$= AT^2\, \varepsilon^{-b/T} \qquad \ldots \qquad (1.7)$$

where A and b are constants.

It is to be noted here that according to F.D. statistics if ϕ is the work done by an electron to surmount the potential barrier and W_i is the energy of an electron in a metal, then the electron will be able to come out of the metal with zero velocity when an energy $(\phi - W_i)$ is given to it. So, Richardson's equation is to be modified as,

$$J = AT^2\, \varepsilon^{-\frac{(\phi - W_i)}{KT}}$$

$$= AT^2\, \varepsilon^{-b/T} \qquad \ldots \qquad (1.8)$$

where $b = (\phi - W_i)$.

1.5 Thermoionic Emitters

Thermoionic emitters are of two different types: (i) *directly heated emitter* or *filamentary emitter* and (ii) *indirectly heated emitter* or *oxide coated emitter*.

In the direct heating, the electric current is applied directly to a wire called filament which itself serves as electron emitter while in indirect heating, electric current is applied to a separate heater located inside a cylindrical cathode that serves as emitter. The arrangement of these two different types of heating is shown in Fig. 1.2.

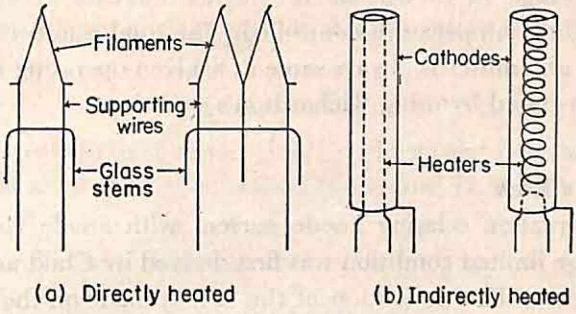

Fig. 1.2

Both alternating or direct current can be used in either methods of heating. Two important directly heated emitters are (*a*) tungsten emitter and (*b*) thoriated tungsten emitter. Indirectly heated cathodes always use oxide coated emitters. Receiving tubes are, in general, indirectly heated types.

1.6 Space Charge

For simplicity, let us consider a vacuum diode consisting of an emitter called cathode and a collector of electrons called anode. At low temperatures, there is no emission of electrons from the cathode surface and hence anode current is zero. As the temperature is raised to emit electrons from the cathode and the anode is disconnected from a source of potential, electrons from the emitter form a cloud in the space. This atmosphere of thermoelectrons that is formed in the interelectrode space between cathode and plate is known as the space charge. Since it is made up of electrons, this atmosphere constitutes a negative charge that has a repelling effect on the electrons being emitted from the cathode. So the effect of the negative space charge alone is to force the emitted electrons back into the cathode by a considerable amount and prevent others from reaching the plate.

However, the space charge does not act alone. It is counteracted by the positive plate which attracts electrons through the space charge. When the plate voltage is low, only those electrons which are nearest to the plate are attracted to it and constitute a small plate current. With the increase of plate voltage, a greater number of electrons is attracted towards the plate and eventually a point is reached when all the electrons emitted from the cathode are attracted to the plate overcoming the effect of space charge completely. With further increase of plate voltage there will be no further increase of current. The current is then temperature controlled. The total number of electrons emitted by an emitter is always same at a given operating temperature and is determined by using Richardson's equation.

1.7 Child's Law

The equation relating anode current with anode voltage under space charge limited condition was first derived by Child and is known as Child's law. The derivation of this law is made on the basis of the following assumptions:

(i) The cathode and anode are plane parallel plates and these are equipotential.

(ii) The cathode temperature is sufficiently high and electrons have zero initial velocity after emission from the cathode.

(iii) The anode voltage is constant for a sufficiently long time so that the anode current can reach a steady value.

(iv) Electrons alone are present in the inter-electrode space.

Since the derivation of this law for the cylindrical shapes of cathode and anode is too complicated, let us consider for simplicity the case of parallel plate configuration. Applying Gauss's theorem to an elementary volume in the inter-electrode space and using Cartesian coordinates we can write,

$$\frac{\delta^2 e}{\delta x^2}+\frac{\delta^2 e}{\delta y^2}+\frac{\delta^2 e}{\delta z^2}=-(\rho/\varepsilon) \quad \ldots \quad (1.9)$$

where, e = potential at the point under consideration,

ρ = density of space charge,

and ε = dielectric constant of the medium considered.

Equation (1.9) is known as Poisson's equation. Let us choose the coordinates in such a manner that X-axis points from cathode to anode and normal to both the surfaces.

Then, $$\frac{\delta^2 e}{\delta y^2}=\frac{\delta^2 e}{\delta z^2}=0 \quad \ldots \quad (1.10)$$

So equation (1.9) reduces to one dimensional form as,

$$\frac{\delta^2 e}{\delta x^2}=-(\rho/\varepsilon) \quad \ldots \quad (1.11)$$

If v is the velocity of the electrons then the current density J can be expressed as,

$$J=-\rho v \quad \ldots \quad (1.12)$$

The negative sign in equation (1.12) indicates the flow of current from cathode to anode. From equations (1.11) and (1.12) we get,

$$\frac{\delta^2 e}{\delta x^2}=\frac{J}{\varepsilon v} \quad \ldots \quad (1.13)$$

Further the velocity v can be obtained from

$$\tfrac{1}{2} m_e v^2 = Q_e e$$

where, Q_e=charge of electron, m_e=its mass;

$$\text{i.e.} \quad v=\sqrt{\frac{2Q_e e}{m_e}} \quad \ldots \quad (1.14)$$

Then by equations (1.13) and (1.14),

$$\frac{\delta^2 e}{\delta x^2}=\frac{J}{\varepsilon}\sqrt{\frac{m_e}{2Q_e e}}$$

$$=K\frac{J}{\sqrt{e}} \quad \ldots \quad (1.15)$$

$$\text{where} \quad K=\frac{1}{\varepsilon}\sqrt{\frac{m_e}{2Q_e}}$$

Multiplying both left-hand and right-hand sides of equation (1.15) by $2\left(\frac{de}{dx}\right) dx$ and integrating we get,

$$\int 2\,\frac{de}{dx}\cdot\frac{d^2 e}{dx^2}\cdot dx=2KJ\int\frac{1}{\sqrt{e}}\cdot\frac{de}{dx}\cdot dx$$

$$\text{or,} \quad \int\frac{d}{dx}\left(\frac{de}{dx}\right)^2 dx=2KJ\int\frac{de}{\sqrt{e}}$$

$$\text{or,} \quad \left(\frac{de}{dx}\right)^2=4KJ\sqrt{e}+K_1 \quad \ldots \quad (1.16)$$

At the cathode surface,

e, $\frac{de}{dx}$ and v are zero.

$$\therefore \quad K_1=0 \quad \ldots \quad (1.17)$$

Hence equation (1.16) reduces to

$$\left(\frac{de}{dx}\right)^2=4KJ\sqrt{e}$$

or, $$\frac{de}{dx}=2\sqrt{KJ}\,e^{1/4}$$

or, $$\int e^{-1/4}\,de=2\sqrt{KJ}\int dx$$

or, $$\tfrac{4}{3}e^{3/4}=2\sqrt{KJ}\,x+K_2 \qquad \ldots \qquad (1.18)$$

Again at $x=0$, $e=0$

$$\therefore\ K_2=0,$$

So equation (1.18) becomes,

$$J^{1/2}=\frac{2}{3\sqrt{K}}\,\frac{e^{3/4}}{x}$$

or, $$J=\frac{4}{9K}\cdot\frac{e^{3/2}}{x^2}$$

$$=\frac{4\varepsilon}{9}\sqrt{\frac{2Q_e}{m_e}}\,\frac{e^{3/2}}{x^2} \qquad \ldots \qquad (1.19)$$

Now, let the distance of the anode from the cathode surface be d and its voltage is e_b.

i.e. at $X=d$,

$$e=e_b.$$

So $$J=\frac{4\varepsilon}{9}\sqrt{\frac{2Q_e}{m_e}}\cdot\frac{{e_b}^{3/2}}{d^2} \qquad \ldots \qquad (1.20)$$

If d is in cm, then J may be expressed in amps/sq. cm. Using the M.K.S. system and substituting the value of ε, Q_e and m_e we have,

$$J=2.33\times10^{-6}\frac{{e_b}^{3/2}}{d^2}\text{ amps/unit area} \qquad \ldots \qquad (1.21)$$

If A be the area of the electrode then the anode current i_b, that is, the current flowing from anode to cathode, is expressed as,

$$i_b=J\,A$$

$$=2.33\times10^{-6}\frac{A}{d^2}{e_b}^{3/2} \qquad \ldots \qquad (1.22)$$

Equation (1.22) is commonly known as 'Child's law'. This is also called as 'Three-halves power equation' or 'Langmuir's equation'.

Examples

1. Electrons emitted from a cathode surface are collected by a plate which is kept at a potential of 10 volts relative to the cathode. If the ratio of charge to mass of an electron is 1.77×10^7 e.m.u. of charge/g calculate its velocity.

If v be the velocity of an electron, we have $\frac{1}{2} m_e v^2 = Q_e e$

where Q_e=charge of an electron,

m_e=mass,

and e=potential.

$$\text{i.e.} \quad v = \sqrt{\frac{2Q_e e}{m_e}}$$

$$\text{Now,} \quad \frac{Q_e}{m_e} = 1.77 \times 10^7 \text{ e.m.u. of charge/g.}$$

$$\text{and} \quad e = 10 \text{ volts}$$

$$= 10^9 \text{ e.m.u. of p.d.}$$

$$\therefore \quad v = \sqrt{2 \times 1.77 \times 10^7 \times 10^9}$$

$$= 1.881 \times 10^8 \text{ cm/s.}$$

2. Two thermoionic emitters having identical dimensions are operated at a fixed temperature of 2400°K. The value of emission constant b for one of the emitters is 52400°K while the work function of the second is 0.6 times that of the first. Calculate the ratio of their emission current densities.

The emission current density for one of the emitters is given by,

$$J_{s_1} = AT^2 \varepsilon^{-b/T}$$

For the other emitter,

$$J_{s_2} = AT^2 \varepsilon^{-0.6b/T}$$

Thus we get,

$$\frac{J_{s_2}}{J_{s_1}} = \varepsilon^{0.4b/T}$$

$$\text{Now,} \quad b = 52400^\circ \text{ K}$$

$$\text{and} \quad T = 2400^\circ \text{ K}$$

$$\therefore \quad \log_e \frac{J_{s_2}}{J_{s_1}} = \frac{0.4 \times 52400}{2400} = 8.733$$

$$\text{or,} \quad \frac{J_{s_2}}{J_{s_1}} = 6194$$

3. An oxide-coated thermoionic emitter is operated at a temperature of 1000°K. Find the value of its emission current density

(given that $A=0.01\times10^4$ amps/sq. m/deg K^2 and $b=12000°K$).

The emission current density can be expressed as,

$$J_s=AT^2\,\varepsilon^{-b/T}$$

Now $A=0{\cdot}01\times10^4$ amps/sq. m/deg K^2

$b=12000°K$

and $T=1000°K$

$$\therefore\quad J_s=0.01\times10^4\times(1000)^2\,\varepsilon^{-(12000/1000)}$$

$$=630 \text{ amps./sq. m.}$$

4. The anode current of a diode is 120 m. amps for an anode potential 100 volts. If its anode potential is changed to 300 volts, what will be the value of the anode current under space charge limited condition?

The anode current i_b can be written as,

$$i_b=K\,e_b{}^{3/2},$$

where e_b is the anode potential.

For the first case,

$$i_b=120\ mA,$$

$$e_b=100 \text{ volts}$$

$$\therefore\quad 120=K\,(100)^{3/2}$$

For the second case,

$$e_b=300 \text{ volts}$$

$$\therefore\quad i_b=K(300)^{3/2}$$

So,
$$\frac{i_b}{120}=\left(\frac{300}{100}\right)^{3/2}$$

$$\therefore\quad i_b=120\times(3)^{3/2}$$

$$=623.5\ mA.$$

So the value of anode current for the second case is 623.5 m.amps.

Self-Test

Read each of the following and provide the appropriate words:

(a) The value of electronic charge is—e.s.u.

(b) Emission of electrons is classified as: thermoionic emission, secondary emission, field emission and — emission.

(c) Indirectly heated cathodes always use — coated emitters.

(d) The atmosphere of thermoelectrons formed in the interelectrodes space between cathode and plate is known as — —.

(e) The equation relating anode current with anode voltage under space charge limited condition is known as — law.

(f) The three-halves power equation is also known as — equation.

Review Questions

1. Explain the four different methods for the emission of electrons from a metallic surface.

2. Derive Richardson's equation from thermodynamical consideration.

3. What are the two different types of thermoionic emitters? —Explain.

4. What is meant by space charge? —Explain clearly.

5. Starting from Poisson's equation derive the Child's law. What are the assumptions required for the derivation of this law?

6. Explain the space charge effect. Show that for a space charge controlled diode the plate current is proportional to three-halves power of the plate voltage.

7. If the p.d. between the cathode and anode of a discharge tube is 50,000 volts, calculate the velocity of an electron inside the tube. (*Ans.* 1.324×10^{10} cm/s.)

8. Find the value of the current density of a thoriated tungsten emitter operated at a temperature of 1900 deg. Kelvin. The values of constant A and b for the emitter are respectively 3×10^4 amps/sq. m/deg. K^2 and 31500 deg. Kelvin. (*Ans.* 6834 amps. /sq. m.)

9. A diode valve gives an anode current of 120 mamps with an anode voltage of 100 volts. Find the value of the anode voltage which will raise the anode current to 339·4 m amps under space charge limited condition. (*Ans.* 200 volts.)

10. In a diode the anode current is 20 m. amps for an anode voltage of 30 volts. Calculate the anode current for an anode voltage of 55.26 volts under space charge limited condition. (*Ans.* 50 m. amps.)

CHAPTER 2

NETWORK THEOREMS

2.1 Introduction

Elements like inductors, resistors and capacitors can never amplify an electrical signal but they have a vital role in electronic circuits containing valves or transistors having amplification properties. Analysis of electronic circuits to get expressions for current, voltage, power, etc. is too complicated unless some methods are properly applied.

An electric network is nothing but an interconnection of electric circuit elements or branches. The current in any part of a network can be easily calculated for a given applied voltage using the two well-known laws of Kirchhoff as stated below:

(i) In any network, the algebraic sum of the currents meeting at a point is zero. Or mathematically,

$$\Sigma I=0 \qquad \ldots \qquad \ldots \qquad (2.1)$$

(ii) In any closed mesh, the algebraic sum of the electromotive forces is equal to the algebraic sum of the products of the resistances R of each part of the mesh and the currents I flowing through them. Mathematically,

$$\Sigma E=\Sigma IR$$

or,

$$\Sigma E-\Sigma IR=0 \qquad \ldots \qquad (2.2)$$

2.2 Some Important Definitions

Before going into the discussion of network theorems it is desired to introduce some important definitions as given below:

Potential and Current Sources—A hypothetical generator used to maintain its value of potential independent of the output current is known as the potential source and is usually indicated by a circle enclosing a wavy line. Similarly, if a hypothetical generator is used to maintain an output current independent of the terminal voltage then it is known as the current source and is indicated by a circle enclosing an arrow.

Active and Passive Networks—If a network contains energy sources as well as other circuit elements it is called an active network while a network containing circuit elements without any energy source is known as the passive network.

DISTRIBUTED AND LUMPED NETWORKS—If in a network, the inductors, resistors and capacitors are not electrically separated (e.g. a transmission line) is called a distributed network. On the other hand, in a lumped network, physically separate inductors, resistors and capacitors are represented.

NODE AND MESH—A group of elements having two terminals is called a branch. A terminal of any branch is called node (or junction) while a set of branches forming a closed path is known as a mesh (or loop).

2.3 Parameters of Four-Terminal Network

The circuit performance of a four-terminal network may be expressed conveniently in terms of the input and output currents and the voltages at the four terminals.

A network connected to a voltage source and a load is shown in Fig. 2.1. The figure indicates the sign convention for the general case.

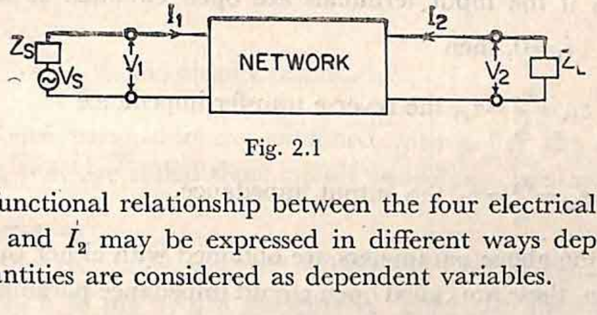

Fig. 2.1

The functional relationship between the four electrical quantities V_1, V_2, I_1 and I_2 may be expressed in different ways depending on which quantities are considered as dependent variables.

(a) *Open-circuit impedance parameters*

If the currents I_1, I_2 are considered as the independent variables, we may write,

$$V_1 = f_1(I_1, I_2) \quad \dots \quad (2.3)$$

$$V_2 = f_2(I_1, I_2) \quad \dots \quad (2.4)$$

which give,

$$dV_1 = \frac{\delta V_1}{\delta I_1} dI_1 + \frac{\delta V_1}{\delta I_2} dI_2 \quad \dots \quad (2.5)$$

and

$$dV_2 = \frac{\delta V_2}{\delta I_1} dI_1 + \frac{\delta V_2}{\delta I_2} dI_2 \quad \dots \quad (2.6)$$

Let us denote,

$$\frac{\delta V_1}{\delta I_1}=z_{11}, \quad \frac{\delta V_1}{\delta I_2}=z_{12}, \quad \frac{\delta V_2}{\delta I_1}=z_{21}, \quad \frac{\delta V_2}{\delta I_2}=z_{22}.$$

Therefore, equations (2.5) and (2.6) can be rewritten as;

$$v_1=z_{11}\,i_1+z_{12}\,i_2 \quad \ldots \quad (2.7)$$

$$v_2=z_{21}\,i_1+z_{22}\,i_2 \quad \ldots \quad (2.8)$$

where the differentials dV_1, dV_2, dI_1 and dI_2 are respectively expressed as v_1, v_2, i_1 and i_2.

If now the output terminals are open circuited to a.c. so that

$i_2=0$, then

$z_{11}=\frac{v_1}{i_1}=z_i$, the input impedance

$z_{21}=\frac{v_2}{i_1}=z_f$, the forward transfer impedance.

Again, if the input terminals are open circuited to a.c. so that

$i_1=0$, then

$z_{12}=\frac{v_1}{i_2}=z_r$, the reverse transfer impedance

$z_{22}=\frac{v_2}{i_2}=z_o$, the output impedance.

Since the above parameters are obtained with either the input or output open, these are called open circuit impedance parameters.

(b) *Short-circuit admittance parameters*

If the voltages V_1, V_2 are considered as the independent variables, we may write

$$I_1=F_1\,(V_1,\,V_2) \quad \ldots \quad (2.9)$$

$$I_2=F_2\,(V_1,\,V_2) \quad \ldots \quad (2.10)$$

or we have,

$$dI_1=\frac{\delta I_1}{\delta V_1}\,dV_1+\frac{\delta I_1}{\delta V_2}\,dV_2 \quad \ldots \quad (2.11)$$

and

$$dI_2=\frac{\delta I_2}{\delta V_1}\,dV_1+\frac{\delta I_2}{\delta V_2}\,dV_2 \quad \ldots \quad (2.12)$$

Let us denote,

$$\frac{\delta I_1}{\delta V_1}=y_{11}, \quad \frac{\delta I_1}{\delta V_2}=y_{12}, \quad \frac{\delta I_2}{\delta V_1}=y_{21}, \quad \frac{\delta I_2}{\delta V_2}=y_{22}$$

Therefore, equations (2.11) and (2.12) can be rewritten as,

$$i_1=y_{11}\,v_1+y_{12}\,v_2 \qquad \dots \qquad (2.13)$$

$$i_2=y_{21}\,v_1+y_{22}\,v_2 \qquad \dots \qquad (2.14)$$

If now the output terminals are short-circuited to a.c. so that $v_2=0$, then

$$y_{11}=\frac{i_1}{v_1}=y_i, \text{ the input admittance,}$$

$$y_{21}=\frac{i_2}{v_1}=y_f, \text{ the forward transfer admittance.}$$

Again, if the input terminals are short circuited to a.c. so that $v_1=0$, then

$$y_{12}=\frac{i_1}{v_2}=y_r, \text{ the reverse transfer admittance,}$$

$$y_{22}=\frac{i_2}{v_2}=y_o, \text{ the output admittance.}$$

Since the above parameters are obtained with either the input or output short, they are called short circuit admittance parameters.

(c) *Hybrid parameters*

A mixture of impedance and admittance parameters gives a third set, known as the hybrid parameters. These we have discussed in the Chapter of Bipolar Transistor.

2.4 Network Theorems

Network problems may be solved by the application of Ohm's and Kirchhoff's laws. In the following subsections some important network theorems are discussed.

2.4.1 Thevenin's Theorem

This theorem as enunciated by Helmholtz and latter by Thevenin is applied to resistive networks. The theorem may be stated as follows:

'Any two-terminal network containing linear impedances and energy sources (generators) can be replaced by an equivalent circuit consisting of a voltage source E' and a series impedance Z'. The value of E' is the open circuit voltage at the terminals and Z' is the impedance measured between the terminals when all the energy sources in the network have been replaced by their internal impedances.

In Fig. 2.2(a) an active network of energy source E is connected to a load Z_L while in Fig. 2.2(b) the passive portion of the network is replaced by its equivalent T section. The theorem then states that the

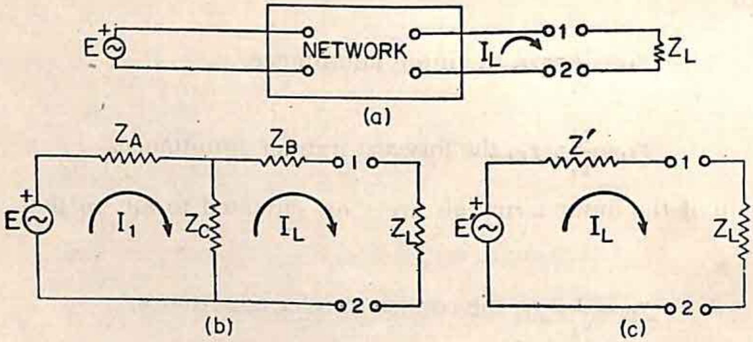

Fig. 2.2

circuit of Fig. 2.2(c) with voltage source E' and impedance Z' will be equivalent to that of Fig. 2.2(b) with identical voltages and currents at Z_L.

For the load current I_L the solution of circuit in Fig. 2.2(b) can be made by considering the mesh equations. We have,

$$E=I_1(Z_A+Z_C)-I_LZ_C \qquad \ldots \quad (2.15)$$

$$0=I_L(Z_B+Z_C+Z_L)-I_1Z_C \qquad \ldots \quad (2.16)$$

In order to get an expression for I_L let us substitute the value of I_1 from equation (2.16) to equation (2.15).

From equation (2.16) we have,

$$I_1=\frac{I_L(Z_B+Z_C+Z_L)}{Z_C} \qquad \ldots \quad (2.17)$$

From equation (2.15),

$$E=\frac{I_L(Z_B+Z_C+Z_L)}{Z_C}(Z_A+Z_C)-I_LZ_C$$

$$\text{or, } I_L=\frac{E}{\frac{(Z_B+Z_C+Z_L)\,(Z_A+Z_C)}{Z_C}-Z_C}$$

$$=\frac{E\,Z_C}{Z_B(Z_A+Z_C)+Z_A\,Z_C+Z_L(Z_A+Z_C)}$$

$$=\frac{E\left(\frac{Z_C}{Z_A+Z_C}\right)}{Z_B+\frac{Z_AZ_C}{Z_A+Z_C}+Z_L} \quad \ldots \quad (2.18)$$

[dividing both numerator and denominator by (Z_A+Z_C)]

Equation (2.18) is the expression for load current that would flow in any value of Z_L.

Again, from Fig. 2.2(b) the open circuit voltage at 1, 2 terminals is,

$$E'=\frac{E}{Z_A+Z_C}.Z_C$$

$$=E\left(\frac{Z_C}{Z_A+Z_C}\right) \quad \ldots \quad (2.19)$$

and if E is short circuited, then

$$Z'=Z_B+\frac{Z_AZ_C}{Z_A+Z_C} \quad \ldots \quad (2.20)$$

By using equations (2.18), (2.19) and (2.20) we get,

$$I_L=\frac{E'}{Z'+Z_L} \quad \ldots \quad (2.21)$$

which is the current expression for network in Fig. 2.2(c). The theorem has, therefore, been established.

2.4.2 Norton's Theorem

Norton suggested a theorem, somewhat similar to that of Thevenin, in which the network is replaced by a constant current generator and a parallel admittance. The theorem may be stated as follows: "Any two terminal network containing linear impedances and energy sources (generators) can be replaced by an equivalent circuit consisting of a current source I' and a parallel admittance Y'. The value of I' is the short circuit current at the terminals and Y' is the admittance measured between the terminals when all the energy sources have been replaced by their internal admittances."

In Fig. 2.3(a) an active network of energy source E is connected to a load Z_L while in Fig. 2.3(b) the network has been converted to the voltage-source equivalent circuit by Thevenin's theorem. The theorem then states that the circuit of Fig 2.3(c) with a constant current generator of value I' will be equivalent to that of Fig. 2.3(b).

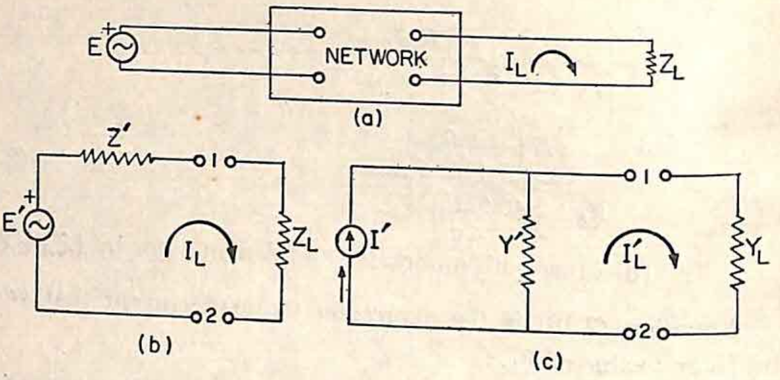

Fig. 2.3

The load current I_L in Fig. 2.3 (b) is given by

$$I_L = \frac{E'}{Z'+Z_L} \quad \dots \quad (2.22)$$

Since the reciprocal of impedance is known as admittance we have,

$$Z' = \frac{1}{Y'} \text{ and } Z_L = \frac{1}{Y_L} \quad \dots \quad (2.23)$$

(where Y' and Y_L are two admittances)

$$\therefore \quad Z'+Z_L = \frac{1}{Y'} + \frac{1}{Y_L} = \frac{Y'+Y_L}{Y'Y_L}$$

$$\text{or,} \quad \frac{1}{Z'+Z_L} = \frac{Y'Y_L}{Y'+Y_L} \quad \dots \quad (2.24)$$

By equations (2.22) and (2.24),

$$I_L = E'\left(\frac{Y'Y_L}{Y'+Y_L}\right)$$

$$= E'Y'\left(\frac{Y_L}{Y'+Y_L}\right) \quad \dots \quad (2.25)$$

Next consider the circuit of Fig. 2.3(c) where the constant current generator I' is in parallel with the admittances Y' and Y_L. Using

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appropriate current division factor, the load current I'_L in the admittance Y_L may be written as,

$$I'_L = I'\left(\frac{Y_L}{Y'+Y_L}\right) \qquad \dots \qquad (2.26)$$

Again, from Fig. 2.3(b), the short circuit current at 1, 2 terminals is,

$$I' = \frac{E'}{Z'} = E'Y' \qquad \dots \qquad (2.27)$$

By equations (2.25) and (2.27) we get,

$$I_L = I'\left(\frac{Y_L}{Y'+Y_L}\right) \qquad \dots \qquad (2.28)$$

Therefore from equations (2.26) and (2.28) we have,

$$I_L = I'_L \qquad \dots \qquad (2.29)$$

which proves the validity of Norton's theorem.

It is found that both Thevenin's and Norton's theorems may be applied to any given network and so their choice is made as required.

2.4.3 Superposition Theorem

The statement of the theorem is as follows: "In a network containing linear impedances and energy sources (generators), the current flowing at any point is the sum of all the currents which would separately flow at that point by each energy source."

For the verification of the theorem, let us consider the simple network with two generators of e.m.f.'s E_1 and E_2, as shown in Fig. 2.4.

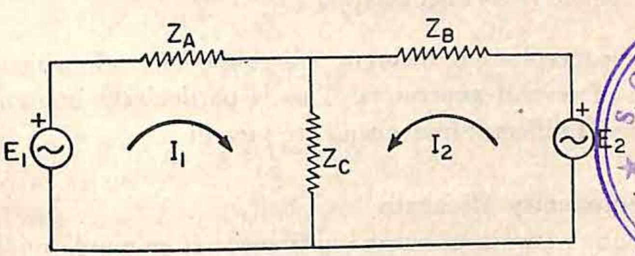

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Fig. 2.4

Let the currents due to E_1 and E_2 acting together are I_1 and I_2 and suppose the currents due to E_1 acting alone be I'_1 and I'_2 and also the currents due to E_2 acting alone be I''_1 and I''_2.

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When both E_1 and E_2 are applied simultaneously we have,

$$E_1=I_1\,(Z_A+Z_C)+I_2Z_C \quad \ldots \quad (2.30)$$

and

$$E_2=I_2(Z_B+Z_C)+I_1Z_C \quad \ldots \quad (2.31)$$

Now, when E_1 is considered alone,

$$E_1=I'_1(Z_A+Z_C)+I'_2Z_C \quad \ldots \quad (2.32)$$

and

$$0=I'_2(Z_B+Z_C)+I'_1Z_C \quad \ldots \quad (2.33)$$

and when E_2 is considered to act alone,

$$0=I''_1(Z_A+Z_C)+I''_2Z_C \quad \ldots \quad (2.34)$$

and

$$E_2=I''_2(Z_B+Z_C)+I''_1Z_C \quad \ldots \quad (2.35)$$

Adding equations (2.32) and (2.34),

$$E_1=(I'_1+I''_1)(Z_A+Z_C)+(I'_2+I''_2)Z_C \quad \ldots \quad (2.36)$$

and adding equations (2.33) and (2.35),

$$E_2=(I'_2+I''_2)(Z_B+Z_C)+(I'_1+I''_1)Z_C \quad \ldots \quad (2.37)$$

It is seen that equations (2.36) and (2.37) are respectively identical with equations (2.30) and (2.31) if

$$I_1=I'_1+I''_1$$

and

$$I_2=I'_2+I''_2 \quad \ldots \quad (2.38)$$

which must then be true.

The superposition theorem simplifies network calculation in presence of several generators. This is particularly important when generators of different frequencies are present.

2.4.4 Reciprocity Theorem

"In any network of linear impedances, if an e.m.f. applies in one mesh produces a certain current in the second mesh, then the same e.m.f. acting in the second mesh will give an identical current in the first mesh."

For the verification of the theorem let us consider the simple arrangement, shown in Fig. 2.5, where a T-network is inserted between a generator and a load.

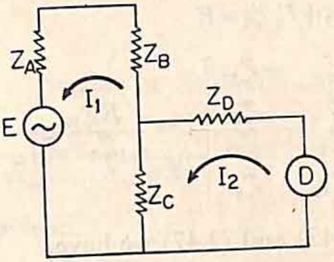


Fig. 2.5

Let E be the source of e.m.f. and D the detector. In the above circuit, let the currents be I_1 and I_2 in the two meshes. Further, say,

$$\mathcal{Z}_1=\mathcal{Z}_A+\mathcal{Z}_B+\mathcal{Z}_C=\text{self-impedance of mesh 1,}$$

$$\mathcal{Z}_2=\mathcal{Z}_C+\mathcal{Z}_D=\text{self-impedance of mesh 2,}$$

and $\mathcal{Z}_{12}=\mathcal{Z}_C=$mutual impedance of mesh 1 and 2.

Applying Kirchhoff's law in the mesh 1 and 2, we have,

$$E=I_1\mathcal{Z}_1-I_2\mathcal{Z}_{12} \quad \ldots \quad (2.39)$$

and

$$0=I_2\mathcal{Z}_2-I_1\mathcal{Z}_{12} \quad \ldots \quad (2.40)$$

From equation (2.39),

$$I_1=\frac{E}{\mathcal{Z}_1}+\frac{\mathcal{Z}_{12}}{\mathcal{Z}_1}I_2 \quad \ldots \quad (2.41)$$

Putting the value of I_1 in equation (2.40),

$$I_2\mathcal{Z}_2-\left(\frac{E}{\mathcal{Z}_1}+\frac{\mathcal{Z}_{12}}{\mathcal{Z}_1}I_2\right)\mathcal{Z}_{12}=0$$

$$\text{or,}\quad I_2\left(\mathcal{Z}_2-\frac{\mathcal{Z}_{12}^2}{\mathcal{Z}_1}\right)=\frac{E\mathcal{Z}_{12}}{\mathcal{Z}_1}$$

$$\text{or,}\quad I_2(\mathcal{Z}_1\mathcal{Z}_2-\mathcal{Z}_{12}^2)=E\mathcal{Z}_{12}$$

$$\therefore\quad I_2=\frac{E\mathcal{Z}_{12}}{\mathcal{Z}_1\mathcal{Z}_2-\mathcal{Z}_{12}^2} \quad \ldots \quad (2.42)$$

Now, interchanging the position of source and detector we get,

$$0=I'_1\mathcal{Z}_1-I'_2\mathcal{Z}_{12} \quad \ldots \quad (2.43)$$

and

$$E=I'_2\mathcal{Z}_2-I'_1\mathcal{Z}_{12} \quad \ldots \quad (2.44)$$

Rearranging equations (2.43) and (2.44) we can write,

$$I_1'Z_1 - I_2'Z_{12} = 0 \qquad \ldots \qquad (2.45)$$

$$-I_1'Z_{12} + I_2'Z_2 = E \qquad \ldots \qquad (2.46)$$

$$\therefore \quad I_1' = \frac{\begin{vmatrix} 0 & -Z_{12} \\ E & Z_2 \end{vmatrix}}{\begin{vmatrix} Z_1 & -Z_{12} \\ -Z_{12} & Z_2 \end{vmatrix}} = \frac{EZ_{12}}{Z_1Z_2 - Z_{12}^2} \qquad \ldots \qquad (2.47)$$

By equations (2.42) and (2.47) we have,

$$I_2 = I_1' \qquad \ldots \qquad (2.48)$$

Therefore with the transposition of the source and detector the current remains same. The source and the detector cannot be interchanged, however, in a special case when they have equal impedances.

2.4.5 Maximum Power Transfer Theorem

This theorem is applicable to all branches of electrical engineering and is particularly important in communication work. The theorem may be stated as follows:

"A two-terminal network will absorb maximum power from a generator if the load impedance is the complex conjugate of the internal impedance of the generator."

For the verification of the theorem let us consider the circuit diagram of Fig. 2.6.

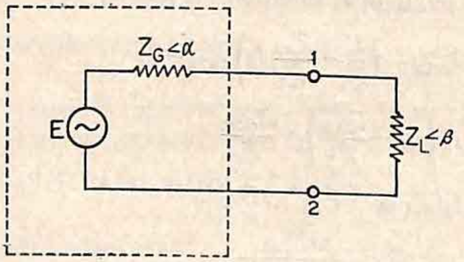


Fig. 2.6

Here, the generator impedance $Z_G \angle \alpha = R_G + jX_G$,

where $\tan \alpha = \dfrac{X_G}{R_G}$

and the load impedance $Z_L \angle\beta = R_L + jX_L$,

where $\tan\beta = \dfrac{X_L}{R_L}$.

Then the current I flowing in the circuit will be,

$$I = \frac{E}{(R_L+R_G)+j(X_L+X_G)} \quad \dots \quad (2.49)$$

$\therefore$ power in the load,

$$P = I^2 R_L$$

$$= \frac{E^2 R_L}{(R_L+R_G)^2+(X_L+X_G)^2} \quad \dots \quad (2.50)$$

Maximising this expression with respect to X_L gives,

$$\frac{\delta P}{\delta X_L} = \frac{-2E^2 R_L (X_L+X_G)}{[(R_L+R_G)^2+(X_L+X_G)^2]^2} = 0 \quad \dots \quad (2.51)$$

So as far as the variation of X_L is concerned, the maximum power will be achieved for $X_L = -X_G$. Then the power in the load becomes

$$P = \frac{E^2 R_L}{(R_L+R_G)^2} \quad \dots \quad (2.52)$$

Again maximising expression (2.50) with respect to R_L we get,

$$\frac{\delta P}{\delta R_L} = \frac{E^2(R_L+R_G)^2 - 2E^2 R_L (R_L+R_G)}{(R_L+R_G)^4} = 0$$

or, $$(R_L+R_G)^2 - 2R_L^2 - 2R_L R_G = 0 \quad \dots \quad (2.53)$$

Hence for $R_L = R_G$, the power will be maximum.

The expression for the maximum power P may then be written as,

$$P = \frac{E^2 R_L}{(2R_L)^2} = \frac{E^2}{4R_L} \quad \dots \quad (2.54)$$

We may thus conclude that the power absorbed by the load will be maximum when the resistive components of both the load and generator impedances are equal and also the reactance of the load has an opposite sign to that of the generator, i.e. when the impedance of the load is the complex conjugate of the internal impedance of the generator.

Self-Test

Read each of the following and provide the appropriate words:

(a) In any network, the algebraic sum of the — meeting at a point is zero.

(b) In a lumped network the inductors, resistors and capacitors are electrically separated. (True/False).

(c) A terminal of any branch is called — and a set of branches forming a closed path is known as a —.

(d) The parameters obtained with either the input or output open are called — parameters.

(e) Thevenin's theorem refers to the equivalence of a network in terms of a constant — generator while Norton's theorem states the equivalence in terms of a constant — generator.

(f) — theorem is particularly important when generators of different frequencies are present.

Review Questions

1. State Kirchhoff's laws.

2. Define the following: (a) potential and current sources, (b) active and passive networks, (c) distributed and lumped networks, (d) node and mesh.

3. Derive expressions for the impedance parameters and admittance parameters of a four-terminal network.

4. State and prove Thevenin's theorem.

5. Make a comparative study of Thevenin's and Norton's theorem.

6. What is 'Superposition Theorem'?—Prove it.

7. With suitable circuit diagram prove the reciprocity theorem and give its statement.

8. State and explain the 'Maximum Power Transfer Theorem'.

9. Give statements of: (a) Thevenin's Theorem, (b) Norton's Theorem and (c) Superposition Theorem.

CHAPTER 3

CIRCUIT THEORY

3.1 Introduction

The flow of electrons in an electrical circuit in which the direction of movement periodically reverses so that the average value over a period becomes zero is called the alternating current. This means an alternating current has a positive and an equal negative maximum value during each periodic time. The number of such complete cycles per second is called the frequency.

The form of the alternating current (I) which changes sinusoidally with time (t) is shown in Fig. 3.1, where $+I_o$ and $-I_o$ represent maximum positive and negative currents in the time period T. The equation for the instantaneous value of an alternating current can be written as,

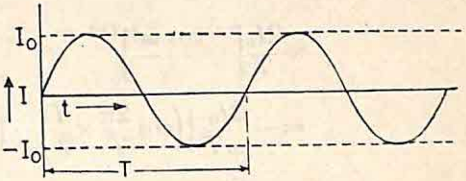


Fig. 3.1

$$I = I_o \sin \omega t, \text{ where } \omega = \text{angular velocity (in radians/s)} = 2\pi/T$$

$$= I_o \sin \frac{2\pi}{T}\, t$$

$$= I_o \sin 2\pi ft \quad (\because f = 1/T) \qquad \ldots \qquad (3.1)$$

Similarly if E_o be the maximum e.m.f. then at any instant of time t the instantaneous value of the e.m.f. E is given by,

$$E = E_o \sin \omega t$$

$$= E_o \sin 2\pi ft \qquad \ldots \qquad (3.2)$$

3.2.1 Mean Current and Mean e.m.f.

For a complete cycle of periodic time T, the average value of an alternating current of instantaneous value $I = I_o \sin \omega t$ is given by,

$$I_{av} = \frac{1}{T}\int_0^T I_o \sin \omega t \, dt$$

$$= \frac{I_o}{T}\left[-\frac{\cos \omega t}{\omega}\right]_0^T$$

$$= \frac{I_o}{T} \cdot \frac{1}{\omega}\left\{\left(-\cos\frac{2\pi}{T}\times T\right)-\left(\cos\frac{2\pi}{T}\times 0\right)\right\}$$

$$= \frac{I_o}{\omega T}(-1+1)=0 \qquad \ldots \qquad (3.3)$$

Thus, the average value over a complete cycle becomes zero. This can alternately be seen in the following way. For the first half of the cycle the average value of current is,

$$\frac{1}{T/2}\int_0^{T/2} I_o \sin\omega t\, dt$$

$$=\frac{2I_o}{T}\left[-\frac{\cos\omega t}{\omega}\right]_0^{T/2}$$

$$=-\frac{2I_o}{\omega T}\left\{\left(\cos\frac{2\pi}{T}\times\frac{T}{2}\right)-\left(\cos\frac{2\pi}{T}\times 0\right)\right\}$$

$$=-\frac{2I_o}{\omega T}\left(-1-1\right)$$

$$=\frac{4I_o}{\frac{2\pi}{T}\cdot T}=\frac{2}{\pi}I_o \qquad \ldots \qquad (3.4)$$

Similarly for the next half of the cycle the average value is

$$\frac{1}{T/2}\int_{T/2}^{T} I_o \sin\omega t\, dt$$

$$=\frac{2I_o}{T}\left[-\frac{\cos\omega t}{\omega}\right]_{T/2}^{T}$$

$$=-\frac{2I_o}{\omega T}\left\{\left(\cos\frac{2\pi}{T}\times T\right)-\left(\cos\frac{2\pi}{T}\times\frac{T}{2}\right)\right\}$$

$$=-\frac{2I_o}{\omega T}(1+1)$$

$$=-\frac{4I_o}{\frac{2\pi}{T}\cdot T}=-\frac{2}{\pi}I_o \qquad \ldots \qquad (3.5)$$

Equations (3.4) and (3.5) indicate that during the two successive halves of the cycle the average currents have equal magnitudes but opposite directions. Conseqeuently, the average value during a complete cycle becomes zero.

By the term mean current or mean e.m.f. in an a.c. circuit is meant the average value of that quantity over a positive half cycle. Thus we can write,

$$I_{mean}=\frac{2I_o}{\pi} \qquad \ldots \qquad (3.6)$$

Similarly,

$$E_{mean}=\frac{2E_o}{\pi} \qquad \ldots \qquad (3.7)$$

3.2.2 R.M.S. Current and R.M.S. e.m.f.

The r.m.s. or root mean square value of an alternating current is defined as the square root of the mean value of the square of that quantity for a complete cycle. Mathematically, the r.m.s. value of current

$$I_{rms}=\sqrt{\bar{I^2}}$$

$$\text{where, } \bar{I^2}=\frac{1}{T}\int_0^T I_0^2 \sin^2 \omega t\, dt$$

$$=\frac{I_0^2}{T}\int_0^T \left(\frac{1-\cos 2\omega t}{2}\right) dt$$

$$=\frac{I_0^2}{T}\left[\frac{t}{2}-\frac{\sin 2\omega t}{4\omega}\right]_0^T$$

$$=\frac{I_0^2}{T}\left[\frac{T}{2}-\frac{\sin\left(2\cdot\frac{2\pi t}{T}\right)}{4\pi}\right]_0^T$$

$$=\frac{I_0^2}{T}\cdot\frac{T}{2}$$

$$=\frac{I_0^2}{2}$$

$$\therefore \quad I_{rms}=\sqrt{\frac{I_0^2}{2}}$$

$$=\frac{I_o}{\sqrt{2}}=0.707\, I_o \qquad \ldots \qquad (3.8)$$

In a similar way,

$$E_{rms}=\frac{E_o}{\sqrt{2}}=0.707\, E_o \qquad \ldots \qquad (3.9)$$

3.2.3 Power and Power Factor

In a d.c. circuit the average power is obtained by the product of load current and the p.d. across the load. In an a.c. circuit also with pure resistive load the average power (W) over a complete cycle is given by,

$$W=\frac{1}{T}\int_0^T E\,I\,dt$$

$$=\frac{1}{T}\int_0^T E_o \sin \omega t \times I_o \sin \omega t\,dt$$

$$=\frac{E_o I_o}{T}\int_0^T \sin^2 \omega t\,dt$$

$$=\frac{E_o I_o}{T}\int_0^T \sin^2 \frac{2\pi}{T}t\,dt$$

$$=\frac{E_o I_o}{T}\cdot\frac{T}{2}$$

$$=\frac{E_o I_o}{2}=\frac{E_o}{\sqrt{2}}\cdot\frac{I_o}{\sqrt{2}}=E_{rms}\cdot I_{rms} \qquad \ldots \qquad (3.10)$$

But with inductive load, i.e., when the circuit contains both the resistance (R) and inductance (L) and an alternating e.m.f. $E=E_o \sin \omega t$ is applied to drive a current through them, the current lags behind the e.m.f. by a constant phase angle a, where $\tan a=\frac{L\omega}{R}$. The instantaneous current is then given by, $I=I_o \sin(\omega t-a)$ and the average power in such a case is,

$$W=\frac{1}{T}\int_0^T E\,I\,dt$$

$$=\frac{1}{T}\int_0^T E_o \sin \omega t\,.\,\mathrm{I}_o \sin(\omega t-a)\,dt$$

$$=\frac{E_o I_o}{T}\int_0^T \sin \omega t\,(\sin \omega t \cos a-\cos \omega t \sin a)dt$$

$$=\frac{E_o I_o}{T}\int_0^T (\sin^2 \omega t \cos a-\sin \omega t \cos \omega t \sin a)\,dt$$

$$=\frac{E_oI_o}{T}\cos\alpha\int_0^T \sin^2\omega t\,dt-\frac{E_oI_o}{T}\sin\alpha\int_0^T\frac{\sin 2\omega t}{2}dt$$

$$=\frac{E_oI_o}{T}\cos\alpha\cdot\frac{T}{2}-\frac{E_oI_o}{2T}\sin\alpha\times 0$$

$$=\frac{E_oI_o}{2}\cos\alpha$$

$$=\frac{E_o}{\sqrt{2}}\cdot\frac{I_o}{\sqrt{2}}\cdot\cos\alpha$$

$$=E_{rms}\cdot I_{rms}\cdot\cos\alpha \qquad \ldots \qquad (3.11)$$

The product $E_{rms}\times I_{rms}$ is called the apparent power and the factor cos α which is to be multiplied to get the average power is known as the power factor of the load.

3.2.4 Form Factor

The form factor (F) of an alternating current may be defined as,

$$F_{current}=\frac{\text{r.m.s. value of current}}{\text{mean value of current}}$$

$$=\frac{I_{rms}}{I_{mean}}=\frac{I_o/\sqrt{2}}{\dfrac{2I_o}{\pi}}=\frac{\pi}{2\sqrt{2}}=1.11 \qquad \ldots \qquad (3.12)$$

Similarly,

$$F_{emf}=\frac{E_{rms}}{E_{mean}}=1.11 \qquad \ldots \qquad (3.13)$$

3.3 Circuit Elements in A.C. Circuits

An electric circuit may contain some or all of the following components, viz., inductor (L), capacitor (C) and resistor (R). Using complex numbers behaviour of an a.c. circuit with (i) L–R, (ii) C–R and (*iii*) L–C–R in series is discussed below.

3.3.1 An A.C. Circuit with Inductor and Resistor in Series

Let a source of sinusoidal e.m.f. of instantaneous value $\mathbf{E}=\mathbf{E}_o\,\mathbf{e}^{j\omega t}$ is applied to a circuit consisting of an inductance L and a resistance R in series (Fig. 3.2), where E may be considered as the real part of E_o (cos $\omega t+j$ sin ωt). The impressed e.m.f. in driving the instantaneous current $\mathbf{I}$ through the circuit will be opposed by the induced back

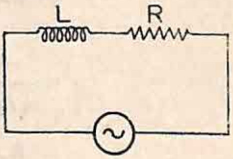


Fig. 3.2

e.m.f. $\left(-L\frac{d\mathbf{I}}{dt}\right)$ developed across the inductance L. So from Ohm's law we can write

$$\mathbf{I}=\frac{\mathbf{E}-L\frac{d\mathbf{I}}{dt}}{R}$$

or,
$$L\frac{d\mathbf{I}}{dt}+R\mathbf{I}=\mathbf{E} \qquad \ldots \qquad (3.14)$$

Let us put as a solution,

$$\mathbf{I}=\mathbf{A}\,e^{jwt} \qquad \ldots \qquad (3.15)$$

where $\mathbf{A}$ may contain both real and imaginary parts.

Then,

$$\frac{d\mathbf{I}}{dt}=j\,\omega\,\mathbf{A}\,e^{jwt}=j\omega\,\mathbf{I}$$

From equation (3.14),

$$jL\omega\,\mathbf{I}+R\mathbf{I}=\mathbf{E}$$

or,
$$(jL\omega+R)\,\mathbf{I}=\mathbf{E}$$

or,
$$\mathbf{I}=\frac{\mathbf{E}}{R+jL\omega}$$

$$=\frac{\mathbf{E}\,(R-jL\omega)}{(R+jL\omega)\,(R-jL\omega)}$$

$$=\frac{\mathbf{E}\,(R-jL\omega)}{R^2+L^2\omega^2} \qquad \ldots \qquad (3.16)$$

Let

$R=a\cos\alpha$, $L\omega=a\sin\alpha$ where a and α are constants.

Then,

$$a=\sqrt{R^2+L^2\,\omega^2} \quad \text{and} \quad \tan\alpha=\frac{L\omega}{R}$$

$$\therefore \qquad \mathbf{I}=\frac{\mathbf{E}\,a\,(\cos\alpha-j\sin\alpha)}{R^2+L^2\,\omega^2}$$

$$=\frac{\mathbf{E}\;(\cos\alpha-j\sin\alpha)}{\sqrt{R^2+L^2\,\omega^2}}$$

$$=\frac{\mathbf{E}\,e^{-j\alpha}}{\sqrt{R^2+L^2\,\omega^2}} \qquad \ldots \qquad (3.17)$$

$$=\frac{\mathbf{E}_o\;e^{j(wt-\alpha)}}{\sqrt{R^2+L^2\,\omega^2}} \quad (\because\; \mathbf{E}=\mathbf{E}_o\,e^{jwt}) \qquad \ldots \qquad (3.18)$$

Equation (3.18) shows that the current lags behind the applied e.m.f. by an angle $\alpha=\tan^{-1}\frac{L\omega}{R}$.

If $E=E_o \cos \omega t$ then in the steady condition the current is given by

$$I=\frac{E_o \cos(\omega t-\alpha)}{\sqrt{(R^2+L^2\omega^2)}} \quad \dots \quad (3.19)$$

$\sqrt{R^2+L^2\omega^2}$ is known as the impedance of the circuit and $L\omega$ is called the reactance of the inductor.

3.3.2 An A.C. Circuit with Capacitor and Resistor in Series

Let a source of sinusoidal e.m.f. of instantaneous value $\mathbf{E}=\mathbf{E}_o\, e^{j\omega t}$ is applied to a circuit consisting of a capacitor C and a resistor R in series (Fig. 3.3). If $\mathbf{I}$ be the instantaneous current then the e.m.f. equation is,

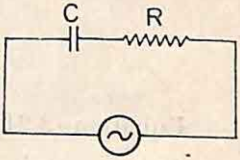


Fig. 3.3

$$\frac{\mathbf{q}}{C}+R\mathbf{I}=\mathbf{E}$$

or,
$$\frac{\int \mathbf{I}\,dt}{C}+R\mathbf{I}=\mathbf{E} \quad \dots \quad (3.20)$$

$$(\because \mathbf{q}=\int \mathbf{I}\,dt)$$

Let us put as a solution,

$$\mathbf{I}=\mathbf{A}\,e^{j\omega t}$$

Then
$$\int \mathbf{I}\,dt=\frac{\mathbf{I}}{j\omega}$$

From equation (3.20)

$$\frac{\mathbf{I}}{jC\omega}+R\mathbf{I}=\mathbf{E}$$

or,
$$\left(\frac{1}{jC\omega}+R\right)\mathbf{I}=\mathbf{E}$$

or,
$$\mathbf{I}=\frac{\mathbf{E}}{R+\frac{1}{jC\omega}}$$

$$=\frac{\mathbf{E}\left(R-\frac{1}{jC\omega}\right)}{R^2+\frac{1}{C^2\omega^2}}$$

Let,

$$R=a\cos\alpha,\quad \frac{1}{C\omega}=a\sin\alpha$$

then

$$a=\sqrt{R^2+\frac{1}{C^2\omega^2}},\quad \tan\alpha=\frac{1}{C\omega R}$$

$$\therefore\qquad \mathbf{I}=\frac{\mathbf{E}\,(a\cos\alpha+ja\sin\alpha)}{R^2+\frac{1}{C^2\omega^2}}$$

$$=\frac{\mathbf{E}\,a\,e^{j\alpha}}{R^2+\frac{1}{C^2\omega^2}}$$

$$=\frac{\mathbf{E}\,e^{j\alpha}}{\sqrt{\left(R^2+\frac{1}{C^2\omega^2}\right)}}\qquad\ldots\qquad(3.21)$$

Equation (3.21) shows that the current leads the e.m.f. by an angle $\alpha=\tan^{-1}\frac{1}{C\omega R}$. Impedance in this case is $\sqrt{R^2+\frac{1}{C^2\omega^2}}$ and $\frac{1}{C\omega}$ is the reactance of the capacitor.

3.3.3 An A.C. Circuit with Inductor, Capacitor and Resistor in Series

Let a source of sinusoidal e.m.f. of instantaneous value $\mathbf{E}=\mathbf{E}_o\,e^{jwt}$ is applied to a circuit consisting of an inductance L, capacitance C and resistance R in series as shown in Fig. 3.4. If $\mathbf{I}$ be the instantaneous current then the e.m.f. equation is,

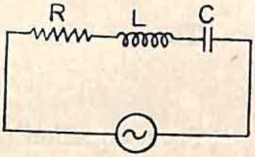


Fig. 3.4

$$L\frac{d\mathbf{I}}{dt}+R\mathbf{I}+\frac{\mathbf{q}}{C}=\mathbf{E}$$

or,

$$L\frac{d\mathbf{I}}{dt}+R\mathbf{I}+\frac{\int\mathbf{I}\,dt}{C}=\mathbf{E}\qquad\ldots\qquad(3.22)$$

Let us put as a solution,

$$\mathbf{I}=\mathbf{A}\,e^{jwt}$$

Then,

$$\frac{d\mathbf{I}}{dt}=j\omega\,\mathbf{A}\,e^{jwt}=j\omega\,\mathbf{I}$$

and

$$\int\mathbf{I}\,dt=\frac{\mathbf{I}}{j\omega}$$

From equation (3.22),

$$jL\omega\,\mathbf{I}+R\mathbf{I}+\frac{\mathbf{I}}{jC\omega}=\mathbf{E}$$

or, $$\left(jL\omega+R+\frac{1}{jC\omega}\right)\mathbf{I}=\mathbf{E}$$

$$\therefore\quad \mathbf{I}=\frac{\mathbf{E}}{R+j\left(L\omega-\frac{1}{C\omega}\right)}\qquad\ldots\quad(3.23)$$

or we can write,

$$\mathbf{I}=\frac{\mathbf{E}\left\{R-j\left(L\omega-\frac{1}{C\omega}\right)\right\}}{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}$$

Let,

$$R=a\cos\alpha,$$

$$L\omega-\frac{1}{C\omega}=a\sin\alpha$$

then

$$a=\sqrt{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}$$

and

$$\tan\alpha=\frac{L\omega-\frac{1}{C\omega}}{R}$$

$$\therefore\quad \mathbf{I}=\frac{\mathbf{E}(a\cos\alpha-ja\sin\alpha)}{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}$$

$$=\frac{\mathbf{E}\,a\,e^{-j\alpha}}{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}$$

$$=\frac{\mathbf{E}\,e^{-j\alpha}}{\sqrt{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}}\qquad\ldots\quad(3.24)$$

Equation (3.24) shows that the current lags behind the applied e.m.f. by an angle $\alpha=\tan^{-1}\dfrac{L\omega-\frac{1}{C\omega}}{R}$. In the above equation,

$\sqrt{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}=Z$ (say), is known as the impedance of the circuit and $\left(L\omega-\frac{1}{C\omega}\right)$ is the reactance. The reactance here is of two different types; the inductive reactance $L\omega$ and the capacitative reactance $\frac{1}{C\omega}$ which are of opposite in sign. If we put the inductive reactance $L\omega=X_L$ and the capacitative reactance $\frac{1}{C\omega}=X_C$ then (X_L-X_C) can be represented by X, where X is the total reactance.

Fig. 3.5 shows how the resistance R, the reactance X and the impedance Z are related to the phase angle a vectorially. The triangle thus obtained is known as the impedance triangle. In the triangle, the resistance R is drawn along the x-axis while the reactances X_L and X_C are drawn along the +ve and −ve y-axis respectively. The vector $Z(=\sqrt{R^2+X^2})$ in this case represents the phase of the impressed e.m.f. and so the diagram is often referred to as a vector impedance diagram.

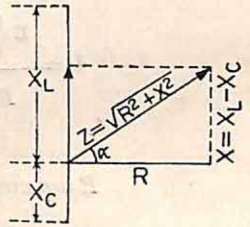


Fig. 3.5

3.3.4 Alternative Treatment for L–R, C–R and L–C–R Circuits in Series

(a) L–R circuit

The e.m.f. equation is,

$$L\frac{dI}{dt}+RI=E=E_0\sin\omega t$$

Let,

$$I=I_0\sin(\omega t-a)$$

$$\therefore\quad \frac{dI}{dt}=\omega I_0\cos(\omega t-a)$$

So we have,

$$\begin{aligned}&L\omega I_0\cos(\omega t-a)+RI_0\sin(\omega t-a)\\&=E_0\sin(\omega t-a+a)\\&=E_0\sin(\omega t-a)\cos a+E_0\cos(\omega t-a)\sin a\end{aligned}$$

Equating coefficients of $\sin(\omega t-\alpha)$ and $\cos(\omega t-\alpha)$ from both sides we get,

$$RI_o=E_o\cos\alpha$$

and

$$L\omega I_o=E_o\sin\alpha$$

i.e.

$$I_o=\frac{E_o}{\sqrt{(R^2+L^2\omega^2)}}$$

and

$$\tan\alpha=\frac{L\omega}{R}$$

$$\therefore\quad I=\frac{E_o}{\sqrt{(R^2+L^2\omega^2)}}\sin(\omega t-\alpha)$$

Taking into consideration the solution of $L\frac{dI}{dt}+RI=0$ which is $I=Ae^{\frac{-Rt}{L}}$ (A=constant), the complete solution for the instantaneous current is

$$I=\frac{E_o}{\sqrt{(R^2+L^2\omega^2)}}\sin(\omega t-\alpha)+Ae^{\frac{-Rt}{L}}$$

The second term will disappear after some lapse of time.

(b) C–R circuit

The e.m.f. equation is

$$\frac{q}{C}+RI=E=E_o\sin\omega t$$

or

$$\frac{I}{C}+R\frac{dI}{dt}=\omega E_o\cos\omega t$$

or

$$\frac{I}{CR}+\frac{dI}{dt}=\frac{\omega E_o}{R}\cos\omega t$$

Let,

$$I=I_o\sin(\omega t+\alpha)$$

$$\therefore\quad \frac{dI}{dt}=\omega I_o\cos(\omega t+\alpha)$$

So we have,

$$\frac{I_o}{CR}\sin(\omega t+\alpha)+\omega I_o\cos(\omega t+\alpha)$$

$$=\frac{\omega E_o}{R}\cos(\omega t+\alpha-\alpha)$$

$$=\frac{\omega E_o}{R}\cos(\omega t+\alpha)\cos\alpha+\frac{\omega E_o}{R}\sin(\omega t+\alpha)\sin\alpha$$

Equating co-efficients of $\sin(\omega t+a)$ and $\cos(\omega t+a)$ from both sides we get,

$$\frac{I_o}{C}=\omega E_o \sin a$$

and

$$I_o=\frac{E_o}{R}\cos a$$

i.e.

$$I_o=\frac{E_o}{\sqrt{R^2+\frac{1}{C^2\omega^2}}}$$

and

$$\tan a=\frac{1}{C\omega R}$$

$$\therefore \qquad I=\frac{E_o}{\sqrt{R^2+\frac{1}{C^2\omega^2}}}\sin\left(\omega t+\tan^{-1}\frac{1}{C\omega R}\right)$$

Taking into consideration the solution of $\frac{I}{RC}+\frac{dI}{dt}=0$ which is $I=Ae^{-\frac{t}{CR}}$ (A=constant), the complete solution for the instantaneous current is,

$$I=\frac{E_o}{\sqrt{R^2+\frac{1}{C^2\omega^2}}}\sin\left(\omega t+\tan^{-1}\frac{1}{C\omega R}\right)+Ae^{-\frac{t}{CR}}$$

Note that in L–R circuit the e.m.f. leads the current by an angle a while in C–R circuit the current leads the e.m.f. by the angle a.

(c) L–C–R circuit

The e.m.f. equation is,

$$L\frac{dI}{dt}+RI+\frac{q}{C}=E_o\sin\omega t$$

or,

$$L\frac{d^2I}{dt^2}+R\frac{dI}{dt}+\frac{I}{C}=\omega E_o\cos\omega t$$

Let,

$$I=I_o\sin(\omega t-a)$$

$$\therefore \qquad \frac{dI}{dt}=\omega I_o\cos(\omega t-a) \quad \text{and} \quad \frac{d^2I}{dt^2}=-\omega^2 I_o\sin(\omega t-a)$$

So we have

$$-L\omega^2 I_o \sin(\omega t-a)+R\omega I_o \cos(\omega t-a)+\frac{I_o}{C}\sin(\omega t-a)$$

$$=\omega E_o \cos(\omega t-a+a)$$

or, $$-\left(L\omega-\frac{1}{C\omega}\right)I_o \sin(\omega t-a)+RI_o\cos(\omega t-a)$$

$$=E_o\cos(\omega t-a)\cos a-E_o\sin(\omega t-a)\sin a$$

Equating coefficients of $\sin(\omega t-a)$ and $\cos(\omega t-a)$ from both sides we get,

$$\left(L\omega-\frac{1}{C\omega}\right)I_o=E_o\sin a$$

and

$$RI_o=E_o\cos a$$

i.e. $$I_o=\frac{E_o}{\sqrt{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}}$$

and

$$\tan a=\frac{L\omega-\frac{1}{C\omega}}{R}$$

$$\therefore \qquad I=\frac{E_o}{\sqrt{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}}\sin(\omega t-a)$$

The complete solution including the transient term is

$$I=\frac{E_o}{\sqrt{R^2+\left(L\omega-\frac{1}{C\omega}\right)^2}}\sin(\omega t-a)+A\,e^{\left(-\frac{R}{2L}+\sqrt{\frac{R^2}{4L^2}-\frac{1}{CL}}\right)t}$$

$$+B\,e^{\left(-\frac{R}{2L}-\sqrt{\frac{R^2}{4L^2}-\frac{1}{CL}}\right)t}$$

where A and B are constants. After some lapse of time in the expression for I, only the steady periodic component remains.

3.4 Resonance

A circuit is called resonant when the frequency of the sinusoidal e.m.f. becomes equal to the natural frequency of the circuit. In practice, a circuit is also said to be resonant when the magnitude of the capacitive reactance is exactly equal to the magnitude of the inductive reactance, i.e. $L\omega = \frac{1}{C\omega}$. Or in other words, in a resonant circuit the reactive component of the impedance vanishes and thereby it behaves as a pure resistance.

For a series resonant circuit the impedance is a minimum while for a parallel resonant circuit it becomes a maximum. A series resonant circuit is sometimes called an acceptor circuit and a parallel resonant circuit is called a rejector circuit.

3.4.1 Series Resonant Circuit

We have found that in an a.c. circuit with inductor, resistor and capacitor in series, the current $\mathbf{I}$ can be expressed as,

$$\mathbf{I} = \frac{\mathbf{E}}{R + j\left(L\omega - \frac{1}{C\omega}\right)} \quad \ldots \quad (3.25)$$

where the impedance $\mathbf{Z}$ is given by,

$$\mathbf{Z} = R + j\left(L\omega - \frac{1}{C\omega}\right) \quad \ldots \quad (3.26)$$

Now, the reactive component will be inductive for $L\omega > \frac{1}{C\omega}$ and capacitive for $L\omega < \frac{1}{C\omega}$. If the value of the inductor or the capacitor is varied such that $L\omega = \frac{1}{C\omega}$, equation (3.26) reduces to,

$$Z = R \quad \ldots \quad (3.27)$$

The impedance then becomes minimum and the circuit is called series resonant.

For a series resonant circuit since

$$L\omega_R = \frac{1}{C\omega_R}$$

or, $$\omega_R = \frac{1}{\sqrt{(LC)}}$$

we have,

$$f_R=\frac{1}{2\pi\sqrt{(LC)}} \qquad \ldots \qquad (3.28)$$

$$(\because\ \omega_R=2\pi f_R)$$

where f_R is the resonant frequency.

3.4.2 Parallel Resonant Circuit

A parallel resonant circuit is shown in Fig. 3.6 where the capacitor C is connected in parallel to the inductor L. To get an expression for current let us first calculate the total impedance of the circuit. Since L and C are connected in parallel their equivalent impedance is found from the relation,

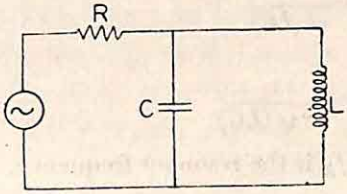


Fig. 3.6

$$\frac{1}{Z_{eq}}=\frac{1}{-j\left(\frac{1}{\omega C}\right)}+\frac{1}{j\omega L}$$

$$=j\omega C+\frac{1}{j\omega L}$$

$$=\frac{-\omega^2LC+1}{j\omega L}$$

or,

$$Z_{eq}=\frac{j\omega L}{1-\omega^2LC} \qquad \ldots \qquad (3.29)$$

where Z_{eq} is the impedance of the LC combination.

The total impedance $\mathbf{Z}$ of the circuit can now be obtained by adding the series combination of R with Z_{eq},

i.e.

$$\mathbf{Z}=R+Z_{eq}$$

$$=R+\frac{j\omega L}{1-\omega^2LC} \qquad \ldots \qquad (3.30)$$

Thus knowing **Z**, the current **I** in the circuit can be written as,

$$\mathbf{I}=\frac{\mathbf{E}}{R+\dfrac{j\omega L}{1-\omega^2LC}} \quad \ldots \quad (3.31)$$

In equation (3.30) for $\omega^2LC=1$, the term $j\omega L/(1-\omega^2LC)$ becomes infinite. The impedance then gives a maximum value and the circuit is called parallel resonant. For a parallel resonant circuit since

$$\omega_R^2\,LC=1$$

or,

$$\omega_R=\frac{1}{\sqrt{(LC)}}$$

we have,

$$f_R=\frac{1}{2\pi\sqrt{(LC)}} \quad \ldots \quad (3.32)$$

where f_R is the resonant frequency.

This is the same relation as obtained in the case of series resonance.

3.5.1 Q-factor

In a resonant circuit the value of the resistance is significant for determining the current in the circuit. This is important since the resistance is also present in the inductor. The effect is similar in both series and parallel resonant circuits. However, the former is mathematically easier and so considered here to illustrate some important features.

The magnitude of the current in the series L–C–R circuit is given by,

$$I=\frac{E}{\sqrt{\left\{R^2+\left(L\omega-\dfrac{1}{C\omega}\right)^2\right\}}} \quad \ldots \quad (3.33)$$

which can be rearranged as,

$$I=\frac{E}{\sqrt{\left\{R^2+(L\omega)^2\left(1-\dfrac{1}{LC\omega^2}\right)^2\right\}}}$$

$$=\frac{E}{R\sqrt{\left\{1+\left(\dfrac{L\omega}{R}\right)^2\left(1-\dfrac{1}{LC\omega^2}\right)^2\right\}}} \quad \ldots \quad (3.34)$$

The ratio of inductive reactance ($L\omega$) to resistance (R) is termed as the Q-factor of the circuit. At resonance the Q-factor may, therefore, be mathematically expressed as,

$$Q_R=\frac{L\omega_R}{R} \qquad \dots \qquad (3.35)$$

3.5.2 Selectivity

If the total resistance in a circuit is low then the curve obtained by plotting current against frequency has a sharp peak. Such a circuit is called sharply resonant or highly selective, On the other hand, if the internal resistance of the generator is high or the resistance of the circuit has a high value then the peak becomes not so pronounced and hence the circuit is said to be poorly selective. So for a sharply resonant series circuit the generator impedance must be sufficiently low.

To compare the selectivity of one circuit with another one must consider the band of frequencies between limits at which the current is minimized by a certain amount, say, $\frac{1}{\sqrt{2}}$ of its maximum value of $\frac{E}{R}$. This happens, as evident from equation (3.33), when

$$L\omega-\frac{1}{C\omega}=\pm R \qquad \dots \qquad (3.36)$$

As shown in Fig. 3.7, let f_1 and f_2 are two frequencies between which the current $I>\frac{E}{\sqrt{2R}}$. Since the power dissipation at f_1 and f_2 is half of the maximum value, these points on the response curve are

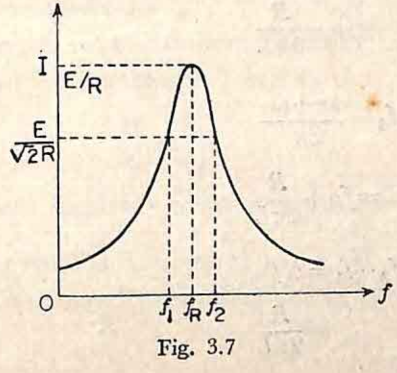


Fig. 3.7

called as half-power points. For f_1 and f_2 let us replace ω in equation (3.36) by $(\omega_R \pm \omega')$. Then we have

$$L(\omega_R \pm \omega') - \frac{1}{C(\omega_R \pm \omega')} = \pm R \qquad \dots \qquad (3.37)$$

Again,

$$L\omega_R = \frac{1}{C\omega_R}$$

i.e.

$$C = \frac{1}{L\omega_R^2} \qquad \dots \qquad (3.38)$$

Substituting the value of C in equation (3.37) we get,

$$L(\omega_R + \omega') - \frac{L\omega_R^2}{(\omega_R + \omega')} = R$$

or,

$$L\omega_R + L\omega' - \frac{L\omega_R}{1 + \frac{\omega'}{\omega_R}} = R$$

or,

$$L\omega_R + L\omega' - L\omega_R\left(1 - \frac{\omega'}{\omega_R}\right) = R$$

$$(\because \omega_R \gg \omega')$$

or,

$$L\omega_R + L\omega' - L\omega_R + L\omega' = R$$

or,

$$2L\omega' = R$$

$$\therefore \quad \omega' = \frac{R}{2L} \qquad \dots \qquad (3.39)$$

Now substituting the value of ω' we have,

$$f_1 = \frac{\omega_R - \omega'}{2\pi}$$

$$= f_R - \frac{R}{4\pi L} \qquad \dots \qquad (3.40)$$

and

$$f_2 = \frac{\omega_R + \omega'}{2\pi}$$

$$= f_R + \frac{R}{4\pi L} \qquad \dots \qquad (3.41)$$

$$\therefore \quad f_2 - f_1 = \Delta f$$

$$= \frac{R}{2\pi L} \qquad \dots \qquad (3.42)$$

Further by equation (3.35) we have,

$$Q_R = \frac{L\omega_R}{R}$$

$$= \frac{L \cdot 2\pi f_R}{R}$$

$$\therefore \qquad f_R = \frac{Q_R R}{2\pi L} \qquad \ldots \qquad (3.43)$$

Dividing equation (3.43) by equation (3.42),

$$\frac{f_R}{\Delta f}$$

$$= \frac{Q_R R}{2\pi L} \cdot \frac{2\pi L}{R}$$

$$= Q_R \qquad \ldots \qquad (3.44)$$

Equation (3.44) gives the selectivity of the circuit for a variation of supply frequency. In practice the supply frequency is altered and the difference in frequency Δf between the half-power points is calculated. When the resonance frequency f_R is divided by this quantity, the Q for the circuit is obtained.

Sometimes the supply frequency is kept constant and the tuning capacitance is varied for getting the Q value. If C_R is the capacitance at resonance then the required relation is,

$$\frac{C_R}{\Delta C} = Q_R \qquad \ldots \qquad (3.45)$$

3.6 A. C. Bridge Circuits

The principle of Wheatstone bridge can also be applied for an a.c. source. Analysis of this circuit proceeds similarly as in d.c., except that here complex impedances and currents are used. The detector is a tuned vibration galvanometer or a telephone receiver. At balance, the voltage across the detector is zero and so

$$\frac{\mathbf{Z}_1}{\mathbf{Z}_2} = \frac{\mathbf{Z}_3}{\mathbf{Z}_4} \qquad \ldots \qquad (3.46)$$

where $\mathbf{Z}_1$, $\mathbf{Z}_2$, $\mathbf{Z}_3$ and $\mathbf{Z}_4$ are the vector impedances of the branches.

The balance condition of equation (3.46) involves the equality of two complex numbers. Such independent balance adjustments of both real and imaginary parts are essential in a.c. bridge circuits. This will be evident from the consideration of the generalized Wheatstone network as shown in Fig. 3.8.

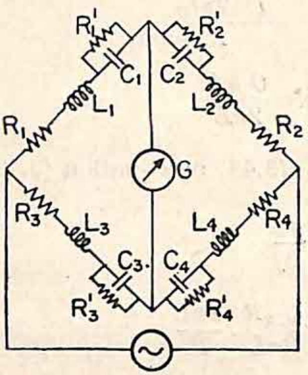


Fig. 3.8

For balance, we can write,

$$\frac{R_1+jL_1\omega+\dfrac{R_1'}{1+jC_1R_1'\omega}}{R_2+jL_2\omega+\dfrac{R_2'}{1+jC_2R_2'\omega}}=\frac{R_3+jL_3\omega+\dfrac{R_3'}{1+jC_3R_3'\omega}}{R_4+jL_4\omega+\dfrac{R_4'}{1+jC_4R_4'\omega}}$$

(a) If $L_1=L_2=L_3=L_4=0$

and

$$R_1'=R_2'=R_3'=R_4'=0$$

we have,

$$\frac{R_1}{R_2}=\frac{R_3}{R_4} \qquad \ldots \quad (3.47)$$

(b) If $R_1=R_2=0$,

$$L_3=L_4=0$$

and

$$R_1'=R_2'=R_3'=R_4'=0$$

We have,

$$\frac{jL_1\omega}{jL_2\omega}=\frac{R_3}{R_4}$$

or,

$$\frac{L_1}{L_2}=\frac{R_3}{R_4} \qquad \ldots \quad (3.48)$$

(c) If

$$R_1=R_2=0,$$

$$L_1=L_2=L_3=L_4=0$$

and

$$R_1'=R_2'=\infty,$$

$$R_3'=R_4'=0$$

We have,

$$\frac{\frac{1}{jC_1\omega}}{\frac{1}{jC_2\omega}}=\frac{R_3}{R_4}$$

or,

$$\frac{C_2}{C_1}=\frac{R_3}{R_4} \quad \dots \quad (3.49)$$

(d) If

$$L_3=L_4=0$$

and

$$R_1'=R_2'=R_3'=R_4'=0$$

We have,

$$\frac{R_1+jL_1\omega}{R_2+jL_2\omega}=\frac{R_3}{R_4}$$

or,

$$R_1R_4+jL_1\omega R_4=R_3R_2+jL_2\omega R_3 \quad \dots \quad (3.50)$$

Equating real and imaginary parts of equation (3.50) we have,

$$R_1R_4=R_3R_2$$

or,

$$\frac{R_1}{R_2}=\frac{R_3}{R_4} \quad \dots \quad (3.51)$$

and

$$L_1\omega R_4=L_2\omega R_3$$

or,

$$\frac{L_1}{L_2}=\frac{R_3}{R_4} \quad \dots \quad (3.52)$$

By equations (3.51) and (3.52),

$$\frac{R_1}{R_2}=\frac{R_3}{R_4}=\frac{L_1}{L_2} \quad \dots \quad (3.53)$$

3.6.1 Inductance Bridge

(i) *Maxwell's bridge*: The circuit diagram of Maxwell's bridge is shown in Fig. 3.9. It is a very early form of bridge used for measurement of inductance in terms of capacitor and resistances.

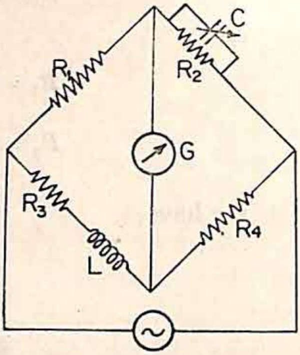


Fig. 3.9

For balance, we have,

$$\frac{\mathbf{Z}_1}{\mathbf{Z}_2}=\frac{\mathbf{Z}_3}{\mathbf{Z}_4}$$

where,

$$\frac{1}{\mathbf{Z}_2}=\frac{1}{R_2}+jC\omega$$

$$\therefore \qquad R_1\left(\frac{1}{R_2}+jC\omega\right)=\frac{R_3+jL\omega}{R_4} \qquad \ldots \qquad (3.54)$$

Equating real and imaginary quantities of equation (3.54) we get,

$$\frac{R_1}{R_2}=\frac{R_3}{R_4}$$

and

$$CR_1=\frac{L}{R_4}$$

or,

$$L=CR_1R_4 \qquad \ldots \qquad (3.55)$$

Equation (3.55) is used to calculate the inductance.

(ii) *Anderson's bridge*: It is one of the most accurate methods for measuring inductance over a wide range. The circuit diagram of the bridge is shown in Fig. 3.10. For simplicity, let R_4 includes the resistance of the inductor L. Then considering Fig. 3.10 we have,

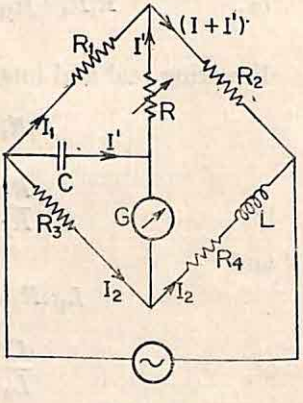


Fig. 3.10

$$\mathbf{I}_1 R_1+(\mathbf{I}_1+\mathbf{I}')R_2=\mathbf{I}_2\,(R_3+R_4+jL\omega) \qquad \ldots \qquad (3.56)$$

$$\mathbf{I}_1R_1=\mathbf{I}'\left(R+\frac{1}{jC\omega}\right) \qquad \ldots \qquad (3.57)$$

and

$$\frac{\mathbf{I}'}{jC\omega}=\mathbf{I}_2\,R_3 \qquad \ldots \qquad (3.58)$$

From equation (3.57),

$$\mathbf{I}_1=\mathbf{I}'\left(\frac{R}{R_1}+\frac{1}{jC\omega R_1}\right) \qquad \ldots \qquad (3.59)$$

From equation (3.58),

$$\mathbf{I}_2=\frac{\mathbf{I}'}{jC\omega R_3} \qquad \ldots \qquad (3.60)$$

Now, equation (3.56) can be rewritten as,

$$\mathbf{I}_1(R_1+R_2)+\mathbf{I}'R_2=\mathbf{I}_2(R_3+R_4+jL\omega)$$

or,
$$\mathbf{I}'\left(\frac{R}{R_1}+\frac{1}{jC\omega R_1}\right)(R_1+R_2)+\mathbf{I}'R_2$$

$$=\frac{\mathbf{I}'}{jC\omega R_3}(R_3+R_4+jL\omega)$$

(putting values of $\mathbf{I}_1$ and $\mathbf{I}_2$)

or,
$$\frac{(R_1+R_2)R}{R_1}+\frac{(R_1+R_2)}{jC\omega R_1}+R_2$$

$$=\frac{R_3+R_4}{jC\omega R_3}+\frac{L}{CR_3} \qquad \ldots \qquad (3.61)$$

Equating imaginary parts of equation (3.61),

$$\frac{R_1+R_2}{R_1}=\frac{R_3+R_4}{R_3}$$

or,
$$\frac{R_1}{R_2}=\frac{R_3}{R_4} \qquad \ldots \qquad (3.62)$$

Equating real parts of equation (3.61),

$$\frac{(R_1+R_2)R}{R_1}+R_2=\frac{L}{CR_3}$$

or,
$$L=CR_3\left[\frac{(R_1+R_2)R}{R_1}+R_2\right]$$

$$=CR_3\left[\left(1+\frac{R_2}{R_1}\right)R+R_2\right]$$

$$=C\left[\left(R_3+\frac{R_2R_3}{R_1}\right)R+R_2R_3\right] \qquad \ldots \qquad (3.63)$$

From equation (3.62) we have,

$$\frac{R_2R_3}{R_1}=R_4$$

and hence by (3.63),

$$L=C[(R_3+R_4)R+R_2R_3] \quad \cdots \quad (3.64)$$

Using equation (3.64) the inductance L can be found out.

3.6.2 Capacitance Bridge

Schering bridge: The circuit diagram of the bridge is shown in Fig. 3.11. It is one of the best methods of determining the capacitance C_1 in terms of the known capacitance C_3. C_4 is a variable capacitor in the circuit.

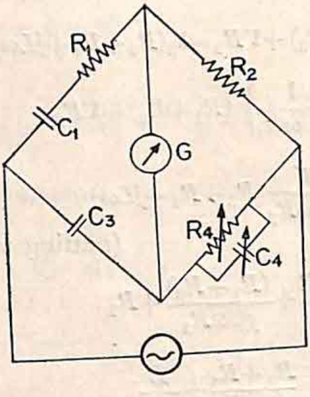


Fig. 3.11

For balance we have,

$$\frac{\mathbf{Z}_1}{\mathbf{Z}_2}=\frac{\mathbf{Z}_3}{\mathbf{Z}_4}$$

or,

$$\frac{\dfrac{1}{jC_1\omega}+R_1}{R_2}=\frac{1}{jC_3\omega}\left(\frac{1}{R_4}+jC_4\omega\right)$$

or,

$$\frac{C_3}{C_1}+jC_3\omega R_1=\frac{R_2}{R_4}+jC_4\omega R_2 \quad \cdots \quad (3.65)$$

Equating real and imaginary parts of equation (3.65),

$$\frac{C_3}{C_1}=\frac{R_2}{R_4}$$

and

$$C_3R_1=C_4R_2$$

i.e., $$\frac{C_3}{C_4}=\frac{R_2}{R_1}$$

By varying C_4 and R_4 the balance point is found. Then the value of the unknown capacitance C_1 is obtained by,

$$C_1=\frac{C_3R_4}{R_2} \qquad \ldots \qquad (3.66)$$

3.7 Ideal Transformer

A transformer in electrical power circuit is normally used to either step up or step down a voltage by its two multiturn coils inductively coupled with each other. Any practical transformer has certain losses, such as, eddy current loss, hysteresis loss, copper loss, flux leakage etc. In an ideal transformer all the magnetic flux from the primary winding is intercepted by the secondary winding. We have considered below what is meant by an ideal transformer.

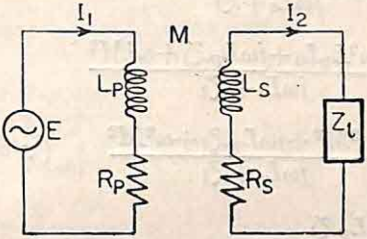


Fig. 3.12

In Fig. 3.12 let the two coils, primary and secondary, are wound on a common magnetic core whose inductances are respectively L_p and L_s. Then,

$$\frac{L_p}{L_s}=\left(\frac{N_p}{N_s}\right)^2 \qquad \ldots \qquad (3.67)$$

where N_p and N_s are the number of turns in the coils.

If all the magnetic flux set up by the first coil links with the other then the mutual inductance M is given by,

$$M=\sqrt{L_pL_s} \qquad \ldots \qquad (3.68)$$

In the figure, as shown, the primary coil is connected to a generator of e.m.f. $\mathbf{E}$ while the secondary coil is connected to an impedance Z_l. By applying Kirchhoff's second law to the two meshes we have,

$$(R_p+j\omega L_p)\mathbf{I}_1-j\omega M\mathbf{I}_2=\mathbf{E} \qquad \ldots \qquad (3.69)$$

and

$$(R_s+j\omega L_s+\mathbf{Z}_l)\mathbf{I}_2-j\omega M\mathbf{I}_1=0 \qquad \ldots \qquad (3.70)$$

From equation (3.70) we get,

$$\mathbf{I}_2=\frac{j\omega M\mathbf{I}_1}{R_s+j\omega L_s+Z_l} \qquad \dots \qquad (3.71)$$

Substituting the value of $\mathbf{I}_2$ in equation (3.69),

$$(R_p+j\omega L_p)\mathbf{I}_1+\frac{\omega^2M^2\mathbf{I}_1}{R_s+j\omega L_s+Z_l}=\mathbf{E}$$

$$\text{or,} \qquad (R_p+j\omega L_p)+\frac{\omega^2M^2}{R_s+j\omega L_s+Z_l}=\frac{\mathbf{E}}{\mathbf{I}_1} \qquad \dots \qquad (3.72)$$

If the resistance is negligibly small compared with the inductance of the winding then the impedance viewed by the generator at the primary terminals is,

$$\mathbf{Z}=j\omega L_p+\frac{\omega^2M^2}{j\omega L_s+Z_l}$$

$$=\frac{-\omega^2L_pL_s+j\omega L_pZ_l+\omega^2M^2}{j\omega L_s+Z_l}$$

$$=\frac{-\omega^2M^2+j\omega L_pZ_l+\omega^2M^2}{j\omega L_s+Z_l} \qquad (\because \quad M=\sqrt{(L_pL_s)})$$

$$=\frac{j\omega L_pZ_l}{j\omega L_s+Z_l}$$

$$=\frac{Z_l}{\frac{L_s}{L_p}+\frac{Z_l}{j\omega L_p}}$$

If L_p is very large so that $j\omega L_p>>Z_l$, then

$$Z=\frac{Z_l}{L_s/L_p}$$

$$=\left(\frac{L_p}{L_s}\right)\cdot Z_l$$

$$=\left(\frac{N_p}{N_s}\right)^2\cdot Z_l \qquad \dots \qquad (3.73)$$

[by equation (3.67)]

The impedance Z in equation (3.73) gives an expression for an ideal transformer.

Examples

1. The equation of an alternating current is $i=50 \sin 400\ \pi t$ amps. What are the frequency and the peak value of the current? What is the r.m.s. value? Calculate also the form factor of the current.

We know that the general equation of an alternating current is,

$$I=I_0 \sin \omega t$$

$$=I_0 \sin 2\pi ft$$

Comparing this with the equation given, viz.,

$$i=50 \sin 400\ \pi t$$

we get,

$$2\pi f=400\ \pi$$

(i) The frequency $f=200$ c.p.s.

(ii) Peak value of current, $I_0=50$ amps.

(iii) The r.m.s. value of current

$$I_{r.m.s.}=\frac{I_0}{\sqrt{2}}=\frac{50}{\sqrt{2}}=35.4 \text{ amps.}$$

(iv) The form factor of current

$$F_{current}=\frac{I_{r.m.s.}}{I_{mean}}$$

Now, $$I_{mean}=\frac{2I_0}{\pi}=\frac{100}{\pi}$$

$\therefore$ $$F_{current}=\frac{50/\sqrt{2}}{\frac{100}{\pi}}=\frac{\pi}{2\sqrt{2}}=1.11.$$

2. An electric lamp of resistance 10 ohms operates an 100 volts d.c. It is required to run the lamp from 220 volts 50 cycles a.c. supply. Calculate the inductance of the choke coil necessary.

We have,

$$I_0=\frac{E_0}{\sqrt{R^2+L^2\omega^2}}=\frac{E_0}{\sqrt{R^2+4\pi^2L^2f^2}}$$

Here, the current required by the lamp,

$$I_0=\frac{100}{10}=10 \text{ amps.}$$

Now

$$E_0=220 \text{ volts, } R=10 \text{ ohms, } f=50 \text{ c.p.s.}$$

$\therefore$ $$10=\frac{220}{\sqrt{100+4\pi^2\times 50^2\times L^2}}$$

or, $$L=6.531\times 10^{-2} \text{ henry.}$$

From equation (3.70) we get,

$$\mathbf{I}_2=\frac{j\omega M\,\mathbf{I}_1}{R_s+j\omega L_s+Z_l} \qquad \ldots \qquad (3.71)$$

Substituting the value of $\mathbf{I}_2$ in equation (3.69),

$$(R_p+j\omega L_p)\mathbf{I}_1+\frac{\omega^2M^2\mathbf{I}_1}{R_s+j\omega L_s+Z_l}=\mathbf{E}$$

or, $$(R_p+j\omega L_p)+\frac{\omega^2M^2}{R_s+j\omega L_s+Z_l}=\frac{\mathbf{E}}{\mathbf{I}_1} \qquad \ldots \qquad (3.72)$$

If the resistance is negligibly small compared with the inductance of the winding then the impedance viewed by the generator at the primary terminals is,

$$\mathbf{Z}=j\omega L_p+\frac{\omega^2M^2}{j\omega L_s+Z_l}$$

$$=\frac{-\omega^2L_pL_s+j\omega L_pZ_l+\omega^2M^2}{j\omega L_s+Z_l}$$

$$=\frac{-\omega^2M^2+j\omega L_pZ_l+\omega^2M^2}{j\omega L_s+Z_l} \qquad (\because \quad M=\sqrt{(L_pL_s)})$$

$$=\frac{j\omega L_pZ_l}{j\omega L_s+Z_l}$$

$$=\frac{Z_l}{\dfrac{L_s}{L_p}+\dfrac{Z_l}{j\omega L_p}}$$

If L_p is very large so that $j\omega L_p>>Z_l$, then

$$Z=\frac{Z_l}{L_s/L_p}$$

$$=\left(\frac{L_p}{L_s}\right)\cdot Z_l$$

$$=\left(\frac{N_p}{N_s}\right)^2\cdot Z_l \qquad \ldots \qquad (3.73)$$

[by equation (3.67)]

The impedance Z in equation (3.73) gives an expression for an ideal transformer.

Examples

1. The equation of an alternating current is $i=50 \sin 400\ \pi t$ amps. What are the frequency and the peak value of the current? What is the r.m.s. value? Calculate also the form factor of the current.

We know that the general equation of an alternating current is,

$$I=I_0 \sin \omega t$$

$$=I_0 \sin 2\pi ft$$

Comparing this with the equation given, viz.,

$$i=50 \sin 400\ \pi t$$

we get,

$$2\pi f=400\ \pi$$

(i) The frequency $f=200$ c.p.s.

(ii) Peak value of current, $I_0=50$ amps.

(iii) The r.m.s. value of current

$$I_{r.m.s.}=\frac{I_0}{\sqrt{2}}=\frac{50}{\sqrt{2}}=35.4 \text{ amps.}$$

(iv) The form factor of current

$$F_{current}=\frac{I_{r.m.s.}}{I_{mean}}$$

Now, $$I_{mean}=\frac{2I_0}{\pi}=\frac{100}{\pi}$$

$$\therefore \qquad F_{current}=\frac{50/\sqrt{2}}{\dfrac{100}{\pi}}=\frac{\pi}{2\sqrt{2}}=1.11.$$

2. An electric lamp of resistance 10 ohms operates an 100 volts d.c. It is required to run the lamp from 220 volts 50 cycles a.c. supply. Calculate the inductance of the choke coil necessary.

We have,

$$I_0=\frac{E_0}{\sqrt{R^2+L^2\omega^2}}=\frac{E_0}{\sqrt{R^2+4\pi^2L^2f^2}}$$

Here, the current required by the lamp,

$$I_0=\frac{100}{10}=10 \text{ amps.}$$

Now

$$E_0=220 \text{ volts, } R=10 \text{ ohms, } f=50 \text{ c.p.s.}$$

$$\therefore \qquad 10=\frac{220}{\sqrt{100+4\pi^2\times 50^2\times L^2}}$$

or, $$L=6.531\times 10^{-2} \text{ henry.}$$

3. An alternating voltage of 100 volts at a frequency of 25 c.p.s. is applied to a circuit containing a resistance of 1.5 ohms and an inductance of 0.01 henry in series. Find the current flowing, the angle of lag and the potential difference across the inductance and resistance.

Here,

$$R=1.5 \text{ ohms}$$
$$L=0.01 \text{ henry}$$
$$E_0=100 \text{ volts}$$
$$f=25 \text{ c.p.s.}$$

(i) The current

$$I_0=\frac{E_0}{\sqrt{R^2+4\pi^2L^2f^2}}$$

$$=\frac{100}{\sqrt{(1.5)^2+4\pi^2(0.01)^2\,(25)^2}}$$

$$=\frac{100}{2.122}=47.12 \text{ amps.}$$

(ii)

$$\tan\,\alpha=\frac{L\omega}{R}=\frac{2\pi fL}{R}$$

$$=\frac{2\pi\times25\times0.01}{1.5}$$

$$=\frac{\pi}{3}=1.0472$$

$$\therefore \quad \alpha=46^\circ 19'.$$

(iii) Voltage across the resistance $=I_0\times R$

$$=47.12\times1.5$$
$$=70.68 \text{ volts}$$

(iv) Voltage across the inductance $=I_0\times L\omega$

$$=47.12\times0.01\times2\pi\times25$$

$$=\frac{47.12\times\pi}{2}=74.01 \text{ volts.}$$

4. An alternating e.m.f. of 200 volts and 50 c.p.s. is applied to a condenser in series with a 20 volts 5 watts metal filament lamp. Find the capacity of the condenser to run the lamp.

We have,

$$I_0=\frac{E_0}{\sqrt{R^2+\dfrac{1}{C^2\omega^2}}}$$

Here,

$$I_0=\frac{\text{power}}{\text{voltage}}=\frac{5}{20}=0.25 \text{ amps.}$$

and so

$$R=\frac{20}{0.25}=80 \text{ ohms.}$$

Also,

$$E_0=200 \text{ volts.}$$

$$f=50 \text{ c.p.s.}$$

Now,

$$0.25=\frac{200}{\sqrt{(80)^2+\dfrac{1}{4\pi^2C^2\,(50)^2}}}$$

or,

$$C=3.999\times10^{-6} \text{ farad}$$

$$=4\ \mu F \text{ (approx.)}$$

5. Calculate the current in a circuit consisting of a condenser of capacity 4 μF and a coil in series when the applied voltage is 220 a.c. 50 c.p.s. and the resistance and inductance are 60 ohms and 3 henries respectively. Find also the power factor of the circuit.

We have,

$$I_0=\frac{E_0}{Z}=\frac{E_0}{\sqrt{R^2+\left(L\omega-\dfrac{1}{C\omega}\right)^2}},$$

where Z is the impedance.

Here,

$$C=4\mu F=4\times10^{-6} \text{ farad}$$

$$E_0=220 \text{ volts}$$

$$f=50 \text{ c.p.s.}$$

$$R=60 \text{ ohms}$$

$$L=3 \text{ henries}$$

Now,

$$I_0=\frac{220}{\sqrt{(60)^2+\left(2\pi\times50\times3-\dfrac{1}{2\pi\times50\times4\times10^{-6}}\right)^2}}$$

$$=\frac{220}{158.8}$$

$$=1.386 \text{ amps.}$$

Power factor,

$$\cos\alpha=\frac{R}{Z}$$

$$=\frac{60}{158.8}$$

$$=0.3780.$$

Self-Test

Read each of the following and provide the appropriate words:

(a) By mean current is meant the average value of that quantity over a — half cycle.

(b) The product $E_{r.m.s.} \times I_{r.m.s.}$ is called the — power.

(c) The form factor of an alternating current may be defined as the ratio of — value of current to the mean value of current.

(d) A circuit is called resonant when the frequency of the sinusoidal e.m.f. becomes equal to the — frequency of the circuit.

(e) For a series resonant circuit the impedance is a —. (minimum/maximum).

(f) The ratio of inductive reactance to resistance is termed as the — of the circuit.

(g) Maxwell's bridge is used for measurement of — in terms of capacitor and resistances.

(h) In an ideal transformer all the magnetic flux from the secondary winding is intercepted by the primary winding. (True/False).

Review Questions

1. Distinguish between the mean value and the root mean square value of an alternating current and find the relation between them.

Deduce an expression for the power consumed in a circuit carrying an alternating current.

2. (a) Define mean, r.m.s. and peak values of an alternating current and establish their relationships for a sinusoidal current.

(b) Define form factor and find its value for an alternating current.

3. Define and explain reactance and impedance of an alternating current circuit.

4. Obtain a relation between current and voltage in an alternating current circuit consisting of resistance R and inductance L.

5. An alternating e.m.f. $e=E \sin \omega t$ is applied to the ends of a coil having a resistance R and self-inductance L. Calculate the current in the circuit.

6. Obtain an expression for current when a sinusoidal e.m.f. is applied to a circuit with capacitor and resistor in series.

7. Find a relation between current and voltage in an a. c. circuit with inductor, capacitor and resistor in series.

8. When a circuit is called resonant? Find expressions for series resonant and parallel resonant circuits.

9. Define Q-factor. Obtain its expression at resonance.

10. When a circuit is called highly selective ? Calculate an expression for the selectivity of the circuit for a variation of supply frequency.

11. (a) Calculate expressions for the inductance L of (i) Maxwell's bridge and (ii) Anderson's bridge.

(b) Explain how the capacitance can be determined using a Schering bridge.

12. Calculate the impedance Z of an ideal transformer.

13. If the maximum instantaneous current has a value of 40 amps., find the current wave equation for a frequency of 50 c.p.s. (*Ans.* $i=40 \sin 314t$)

14. The equation of an alternating current is $i=50 \sin 400 \pi t$. What are the frequency and the peak value of the current? What is the r.m.s. value? (*Ans.* 200 c.p.s., 50 amps., 35.36 amps.)

15. An alternating e.m.f. of 200 volts and 50 c.p.s. is applied to a condenser in series with a 20 volts 5 watts lamp. Find the capacity of the condenser required to run the lamp. (*Ans.* $4\mu F$)

16. An electric lamp which runs at 100 volts d.c. and 10 amps current is connected to 200 volts a.c. mains of 50 c/s frequency and current is found to be 15 amps, Calculate the inductance of the lamp. (*Ans.* 0.028 H)

17. An electric lamp which runs at 100 volts d.c. and 10 amps current is connected to 200 volts 50 cycles a.c. mains. Calculate the inductance of the choke to be used in series. (*Ans.* 0.055 H)

18. Calculate the resistance which must be connected in series with an inductance of 0.2 henry in order that the phase difference between the current and e.m.f. may be 45° when the frequency is 60 cycles per second. (*Ans.* 75.39 ohms)

19. A choke of inductance 0.005 henry, a condenser of capacity 600 μF and a heating coil of resistance 2 ohms are connected in series. Find the value of current in the circuit when a p.d. of 100 volts at 50 cycles per second is applied to it. (*Ans.* 23.7 amps.)

CHAPTER 4

VACUUM TUBES

4.1 Introduction

Vacuum tubes ushered in the age of electronics. Now-a-days though vacuum tubes have been upstaged by solid-state devices like diodes, transistors and integrated circuits, they are still used in various electronic equipments. Of course, vacuum tubes have undergone many changes since the introduction of the Fleming valve. The early tubes were physically large and complicated in operation while modern production have transformed these into small in size with high efficiency.

4.2 Classification of Vacuum Tubes

Vacuum tubes are classified in a number of ways as discussed below:

(i) *Depending on the number of electrodes*: (a) Diode has two electrodes: an anode and cathode. (b) Triode has three electrodes: anode, cathode and control grid. (c) Tetrode has four electrodes: anode, cathode, control grid and screen grid. (d) Pentode has five electrodes: anode, cathode, control grid, screen grid and suppressor grid. Similarly hexode has six electrodes, heptode has seven electrodes and so on.

(ii) *Depending on the presence or absence of gas*: (a) High vacuum tubes: After mounting of the electrodes in the tube envelope, the gas is removed from the electron tube with a vacuum pump of the order of 10^{-8} atmosphere. (b) Gas tubes: After evacuation an inert gas is inserted within the tube envelope.

(iii) *Depending on the type of cathode used*: (a) Thermoionic tubes: In these tubes cathode is heated for emission of electrons. (b) Electron multiplier tubes: Electron emission at a number of electrodes, called dynodes, takes place due to secondary emission. (c) Cold cathode tubes: Electron emission is obtained by high field. (d) Photo tubes: Cathode emits electrons when light falls on it.

4.3 Diode Valve

The term 'di-ode' means two electrodes. The valve consists essentially of a cathode which serves as an emitter of electrons surrounded by a plate or anode which acts as a collector of electrons. Both the electrodes of the valve are sealed inside an evacuated glass or metallic envelope. The emitter may be either directly or indirectly heated type. A diagram of the directly heated diode is shown in Fig. 4.1(a) and

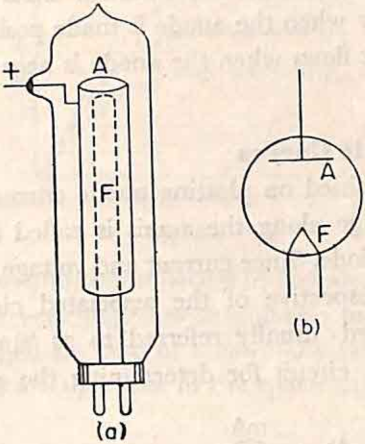


Fig. 4.1

its schematic symbol in Fig. 4.1(b). In the figure, *F* is the filament surrounded by a hollow cylinder *A* known as the anode. The anode is usually made of nickel, molybdenum, graphite, iron etc.

4.3.1 Operation

From the basic law of electricity we know that like charges repel and unlike charges attract each other. Electrons emitted from the cathode surface may be either attracted to or repelled from the anode depending on whether the anode is charged positively or negatively. When the anode *A* is kept at a positive potential relative to the filament *F* by means of a high tension battery as shown in Fig. 4.2(a), electrons are able to move from cathode to anode owing to an attrac-

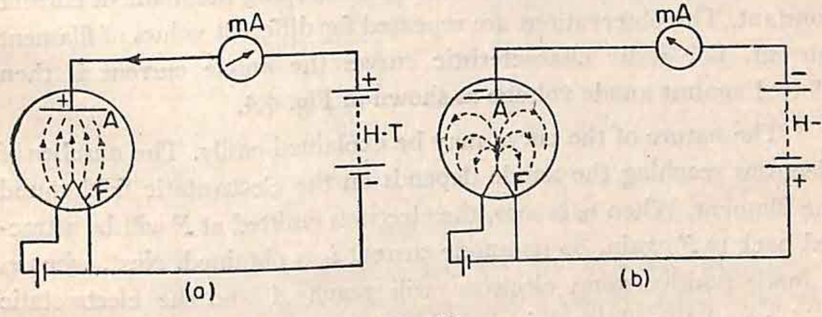


Fig. 4.2

tive effect of the electrons and the valve is said to conduct. But if *A* is maintained at a negative potential relative to *F*, as shown in Fig. 4.2(b), no electrons would reach at *A* due to the repulsive effect on them and so the valve would not conduct. Thus the anode current flows in a diode only when the anode is made positive with respect to filament. No current flows when the anode is negative with respect to filament.

4.3.2 Characteristic Curves

The curves obtained on plotting anode current along the *y*-axis against anode voltage along the *x*-axis is called the current-voltage characteristics of a diode. Since current and voltage involved pertain to the tube alone, irrespective of the associated circuits, the characteristics thus obtained usually referred to as 'static characteristics'. Fig. 4.3 illustrates a circuit for determining the static characteristic curves of a directly heated diode. In the figure, the anode *A* is kept at a positive potential relative to *F* by means of a H. T. battery. The anode current i_b is read on the milliammeter in the circuit.

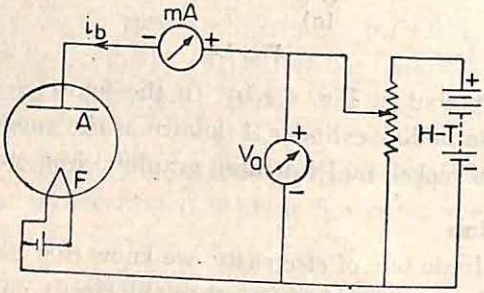


Fig. 4.3

The anode voltage e_b is gradually increased in regular steps and at each step the anode current i_b is recorded keeping the filament current constant. The observations are repeated for different values of filament current. For static characteristic curves the anode current is then plotted against anode voltage as shown in Fig. 4.4.

The nature of the curve may be explained easily. The number of electrons reaching the anode depends on the electrostatic field round the filament. When e_b is zero, the electrons emitted at *F* will be attracted back to *F* again. So no anode current i_b is obtained. Next, when e_b is made positive some electrons will reach *A* and the electrostatic field round the filament is determined by the anode potential e_b. In practice, for any given value of anode voltage a balance is reached at a certain value of anode current when the number of electrons emitted become equal to the numbers collected by the anode. It may be mentioned here that at very high anode voltages oxide-coated cathodes may become damaged because of abnormally large emission. Generally, electron tubes are operated in the space charge limited (low e_b) region.

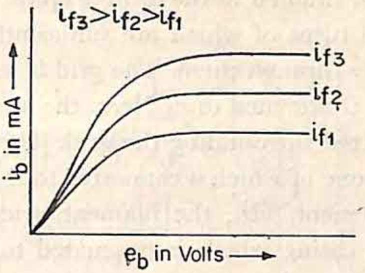


Fig. 4.4

4.4 Triode Valve

The triode valve, as the name implies, contains three electrodes: a cathode of either filament or indirectly heated type, a control grid and an anode. The control grid was first introduced in 1907 by Lee de Forest. It is usually made by a spiral of fine wire placed between the cathode and anode, usually close to the cathode.

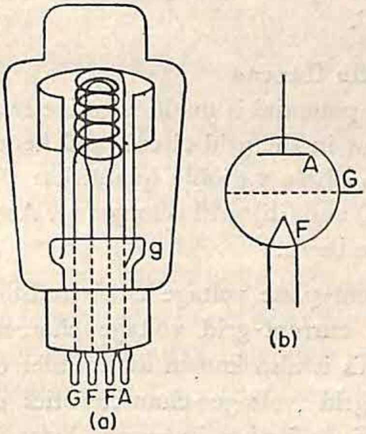


Fig. 4.5

The components of a triode valve and its schematic symbol are shown in Fig. 4.5. The filament is made by a fine tungsten wire, the two terminals of which are sealed in a glass base g and finally connected to two long pins (F, F). Around this filament the grid made by molybdenum wire is situated in the form of spiral as shown; the interspaces between the turns of which are sufficiently wide so that electrons can flow easily through them. The grid is sealed to the base and connected to a pin G attached to it. Next, the anode which is a nickel cylinder is constructed surrounding the grid. This is supported on the base by two wires, one of which is connected to A attached to the base. The whole arrangement, viz., the filament, grid and the anode are enclosed in a glass casing which is evacuated to a pressure of about 10^{-6} mm.

4.4.1 Function of Control Grid

Since the control grid is usually placed close to the cathode, the potential applied to the grid has a greater effect on the electric field inside the tube. The grid, therefore, has a controlling effect on the plate current. The control grid in operation is kept at a negative potential with respect to the cathode. As a result, it does not draw any current and consume power.

As the voltage applied to the grid is made gradually negative, the space current also reduces. Ultimately a certain value is reached when the space current and hence the plate current becomes zero. Such a grid voltage at which plate current vanishes is known as 'cut-off grid voltage'.

4.4.2 Characteristic Curves

When the grid potential is made negative relative to the cathode, electrons do not flow in the grid circuit and hence $i_c=0$. In a triode valve then we have three variable quantities: (i) plate current (i_b), (ii) plate voltage (e_b) and (iii) grid voltage (e_c). Accordingly three types of characteristics are there:

(a) Plate current–plate voltage characteristics, or plate characteristics. (b) Plate current-grid voltage characteristics or 'mutual characteristics'. This is also known as 'transfer characteristics'. And (c) Plate voltage–grid voltage characteristics or 'constant current characteristics'. This is further known as 'amplification characteristics'.

Since the characteristics refer to the tube alone without any allied circuit, the curves such obtained are known as static characteristic curves. The basic circuit diagram for finding the static characteristic of a triode is given in Fig. 4.6.

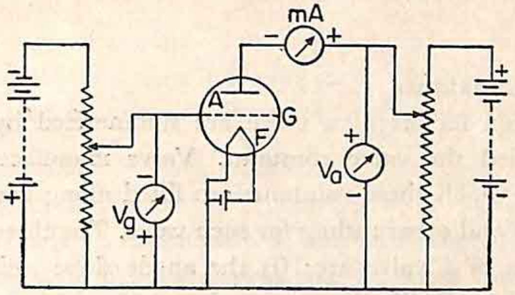


Fig. 4.6

Plate Characteristics: When the grid voltage e_c is made constant and the plate voltage e_b is varied, the plate current i_b will also change. The curve connecting plate current (i_b) with the plate voltage (e_b) is called the plate characteristic curve corresponding to that e_c. If e_c is changed to different values and i_b and e_b are altered, we may get different characteristic curves. A group of characteristic curves, such obtained, have shown in Fig. 4.7(a).

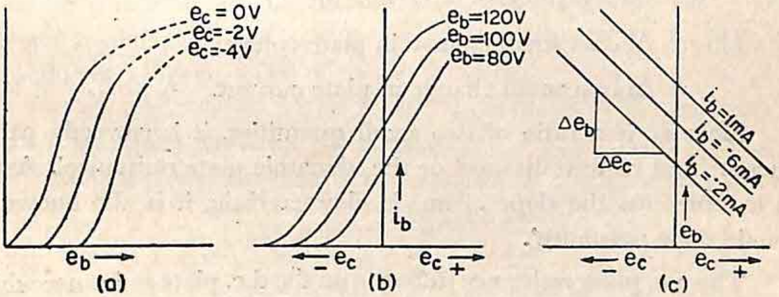


Fig. 4.7

Mutual Characteristics: For a fixed anode voltage (e_b), if e_c is varied and the corresponding i_b is noted we may draw (i_b–e_c) curve as shown in Fig. 4.7(b). The curves such obtained are known as mutual characteristics of a triode valve. When the grid voltage is increased on the positive side, each of these curves will first run parallel and finally approach the saturation value. The mutual characteristics are curved at their lower part and fairly straight and parallel for major portions.

Amplification Characteristics: The amplification characteristics or the constant current characteristics of a triode are shown in Fig. 4.7(c).

These may be obtained from the plate characteristics by drawing horizontal line for constant plate current and grid voltage at each intersection.

4.4.3 Valve Constants

The design factors of a valve are summarized by a series of numbers, called the valve constants. Valve manufacturers publish a manual in which these constants are listed along with the characteristic curves and other ratings for each valve. The three most important constants of a valve are: (i) the anode slope resistance or the a.c. plate resistance, (ii) the transconductance or the mutual conductance, and (iii) the amplification factor.

(i) Plate Resistance (r_p)

This is defined as the ratio of a small change in plate voltage to the corresponding change in plate current, when the grid voltage is kept constant. Mathematically,

A.C. Plate Resistance,

$$r_p = \frac{\delta e_b}{\delta i_b} = \frac{\Delta e_b}{\Delta i_b} \bigg|_{e_c = \text{constant}} \quad \ldots \quad (4.1)$$

where Δe_b=a small change in plate voltage,

Δi_b=a small change in plate current.

Since r_p is a ratio of two small quantities, it is correctly called 'incremental plate resistance' or the 'dynamic plate resistance'. Again as it represents the slope of anode characteristic, it is also known as 'anode slope resistance'.

The a.c. plate resistance differs from the d.c. plate resistance which is the ratio of the plate voltage to plate current, i.e., e_b/i_b. The d.c. plate resistance is also known as the static plate resistance of the valve. The unit of plate resistance is ohm.

(ii) Transconductance (g_m)

This is defined as the ratio of a small change in plate current to the corresponding change in control grid voltage, when the plate voltage is kept constant. Mathematically,

Transconductance,

$$g_m = \frac{\delta i_b}{\delta e_c} = \frac{\Delta i_b}{\Delta e_c} \bigg|_{e_b = \text{constant}} \quad \ldots \quad (4.2)$$

where Δi_b=a small change in plate current,

Δe_c=a small change in grid voltage.

Since the transconductance relates a quantity on the plate side to a quantity on the grid side it is also called 'mutual conductance'. The unit of mutual conductance is expressed in mho (Ohm spelled backward).

(iii) Amplification Factor (μ)

This is defined as the ratio of a small change in plate voltage to the corresponding change in grid voltage, when the plate current is kept constant. Mathematically,

Amplification factor,

$$\mu=\frac{\delta e_b}{\delta e_c}=\frac{\Delta e_b}{\Delta e_c}\bigg/ i_b=\text{constant} \qquad \ldots \qquad (4.3)$$

where Δe_b=a small change in plate voltage,

Δe_c=a small change in grid voltage.

To determine the amplification factor it is therefore required to change the plate voltage by a certain amount, record the change in plate current and then change the grid voltage by an amount just to attain the previous value of the plate current.

4.4.4 Relation between r_p, g_m and μ

We can write the mathematical form of the amplification factor as,

$$\mu=\frac{\delta e_b}{\delta e_c}=\frac{\delta e_b}{\delta i_b}\times\frac{\delta i_b}{\delta e_c}$$

$$=r_p\times g_m \qquad \ldots \qquad (4.4)$$

That is the amplification factor is equal to the product of plate resistance and mutual conductance. The three valve constants are thus interrelated in accordance with their definition.

4.5 Tetrode

A tetrode valve has two grids in addition to cathode and anode. The first one, as mentioned before, is called the control grid while the second grid is known as the screen grid. In the construction, the screen grid is placed between the control grid and the plate and thus avoids the undesirable grid-to-plate capacitance. The schematic symbol of a tetrode valve is shown in Fig. 4.8.

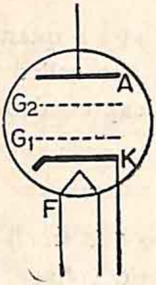


Fig. 4.8

4.5.1 Functions of Screen Grid

The screen grid of a tetrode valve is usually maintained at a high potential value, even sometimes greater than that of the plate. The screen grid of a tetrode valve has two important functions. First, it being maintained at a positive potential, helps to overcome the space charge effect and hence increases the plate current and mutual conductance. Secondly, when the valve is used as an amplifier, the screen grid eliminates the evil effect of interelectrode capacitance between the control grid and the anode.

4.5.2 Characteristic Curves

The circuit diagram for studying the characteristic curves of a tetrode is shown in Fig. 4.9. In this valve since flow of electrons takes

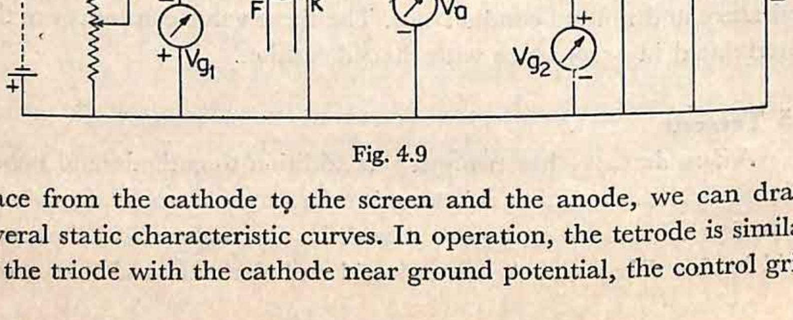


Fig. 4.9

place from the cathode to the screen and the anode, we can draw several static characteristic curves. In operation, the tetrode is similar to the triode with the cathode near ground potential, the control grid at a small negative value while the screen grid and the plate at a fairly high positive values. The positive voltage applied to the screen helps to accelerate the electrons to the plate.

In order to study the characteristic curves of a tetrode, the screen grid voltage (e_{c2}) is kept at a fixed high value. Then for a particular control grid voltage (e_{c1}) the plate voltage e_b is increased in steps and the corresponding screen grid current i_{c2} and the plate current i_b are noted. The experiment is repeated for different control grid voltages and the curves as shown in Fig. 4.10 are obtained. In the figure the space current, which is the sum of i_b and i_{c2}, is found to be constant. This happens because the screen grid screens the plate from both the control grid and the cathode, as a result the field of the plate does not penetrate through the screen grid and hence no effect on space current. That is why the total space current (i_b+i_{c2}) remains almost constant in spite of increase in plate voltage.

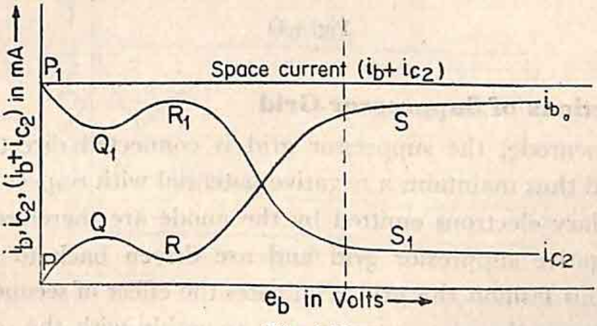


Fig. 4.10

In Fig. 4.10, as shown, with the increase of plate voltage, plate current increases at first as represented by *PQ*, after which in the portion *QR* of the curve it goes to decrease. This means that the tube behaves as a 'negative resistance'. This phenomenon is known as 'dynatron effect'. It is seen from the figure that when the plate current decreases, screen current begins to increase. This strange behaviour happens due to the emission of secondary electrons. What happens is that when the plate voltage is raised, electrons are speeded up sufficiently to dislodge loosely held electrons within the plate and project them as secondary electrons between the plate and the screen grid. These secondary electrons go to the screen grid as its potential is more positive than that of the plate and thus decreasing the anode current and increasing the screen current.

4.6 Pentodes

A pentode valve has five electrodes. These are: (i) cathode, (ii) control grid, (iii) screen grid, (iv) suppressor grid, and (v) plate. In the construction of a pentode the suppressor grid is placed between the screen grid and the plate as shown in the schematic symbol of Fig. 4.11. Since the performance of a pentode is much superior to that of a tetrode, the former is widely used in preference to tetrode.

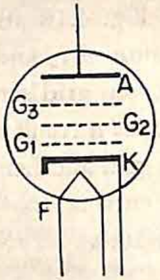


Fig. 4.11

4.6.1 Functions of Suppressor Grid

In a pentode, the suppressor grid is connected directly to the cathode and thus maintains a negative potential with respect to anode. The secondary electrons emitted by the anode are therefore repelled by the negative suppressor grid and are driven back to the plate again. In this fashion the grid eliminates the effect of secondary electrons and hence the plate current rises smoothly with the increase of plate voltage.

The addition of suppressor grid also increases the shielding action between the plate and the control grid and thus reduces the grid to plate capacitance. Because of high screening, the plate current is little affected by the plate voltage and so both the plate resistance and the amplification factor of a pentode become extremely high.

4.6.2 Characteristic Curves

The circuit diagram for studying the characteristic curves of a pentode is shown in Fig. 4.12. Here also, as in the case of a tetrode, the screen grid is kept fixed at a high potential. Then for a particular control grid voltage, the plate voltage is altered in regular steps and the corresponding screen grid and the plate currents are noted. The

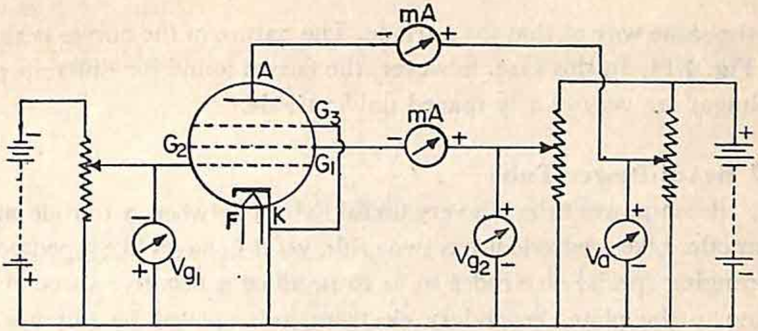


Fig. 4.12

nature of the curve thus obtained is shown in Fig. 4.13. For a pentode also the space current (i_b+i_{c2}) is plotted against the plate voltage.

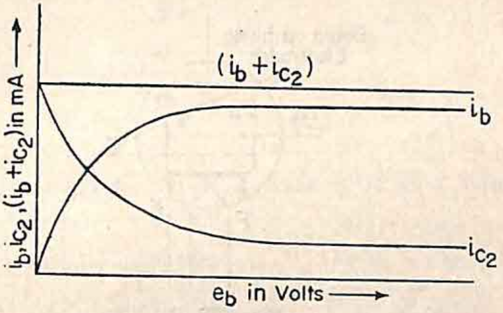


Fig. 4.13

It is seen that the kink in the plate characteristics of the tetrode is eliminated here as the effect due to secondary emission has been suppressed.

The mutual characteristic curves for a pentode may be obtained

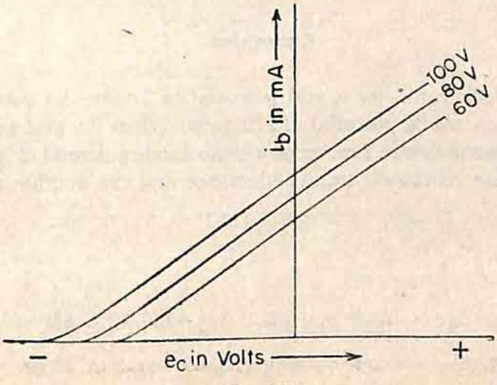


Fig. 4.14

in the same way as that for a triode. The nature of the curves is shown in Fig. 4.14. In this case, however, the curves found for different plate voltages are very closely spaced unlike triode.

4.7 Beam-Power Tube

Beam-power tube is a very useful hybrid between a tetrode and a pentode. Like a tetrode it has two grids, yet it behaves like a pentode by arranging special electrodes so as to produce a negative space charge close to the plate. Secondary electrons are repelled by this negative space charge and back to the plate again. Therefore it is similar to the behaviour of a suppressor grid in a pentode. The schematic symbol of a beam-power tube is shown in Fig. 4.15.

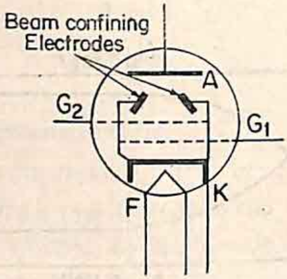


Fig. 4.15

Beam-power tube is superior to that of a pentode as it gives higher plate efficiency and higher power output for a given harmonic distortion. Moreover, it gives a small ratio of screen grid current to the plate current than in a pentode.

Examples

1. In a triode valve, for a grid potential of 2 volts the output current shows 5 m. amps with an anode potential of 220 volts. When the grid potential is changed to 4 volts the current rises to 7 m. amps with an anode potential of 260 volts. Calculate the value of plate resistance, transconductance and the amplification factor of the valve.

We have,

Change in anode potential, $\Delta e_b=260-220=40$ volts

Change in anode current, $\Delta i_b=7-5=2$ m. amps.

Change in grid potential, $\Delta e_c=4-2=2$ volts.

By definition,

$$\text{Plate resistance,}\quad r_p=\frac{\Delta e_b}{\Delta i_b}$$

$$=\frac{40}{2\times10^{-3}}\text{ ohms}$$

$$=20\times10^{3}\text{ ohms.}$$

$$\text{Transconductance,}\quad g_m=\frac{\Delta i_b}{\Delta e_c}$$

$$=\frac{2\times10^{-3}}{2}\text{ mhos}$$

$$=10^{-3}\text{ mhos.}$$

$$\text{Amplification factor,}\quad \mu=\frac{\Delta e_b}{\Delta e_c}$$

$$=\frac{40}{2}$$

$$=20$$

2. Find the amplification factor of a valve if its plate resistance is 20 K and mutual conductance is 2 m. amps/volt.

The mathematical relation between μ, r_p and g_m can be written as,

$$\mu=r_p\times g_m$$

Here,

$$r_p=20\text{ K}$$

$$=20\times10^{3}\text{ ohms.}$$

$$g_m=2\text{ m. amps/volt}$$

$$=2\times10^{-3}\text{ mhos.}$$

$$\therefore\quad \mu=20\times10^{3}\times2\times10^{-3}$$

$$=40.$$

Self-Test

Read each of the following and provide the appropriate words:

(a) The early tubes were physically small and simple in operation. (True/False).

(b) No current flows when the anode is — with respect to cathode.

(c) The curve obtained on plotting anode current against anode voltage is called the — characteristic.

(d) At very high anode voltages oxide coated cathodes may be damaged due to abnormally — emission (large/small).

(e) The control grid in operation is kept at a — potential with respect to cathode.

(f) In a triode we have three variable quantities: plate current, plate voltage and — voltage.

(g) The ratio of a small change in plate current to the corresponding change in control grid voltage is called —.

(h) In the construction of a tetrode valve the screen grid is placed between the control grid and the —.

(i) Beam power tube is superior to that of a pentode as it gives higher — efficiency and higher — output.

Review Questions

1. How vacuum tubes can be classified?

2. Describe a diode valve. What are the static characteristics of a diode?

3. Describe the construction of a triode valve. Clearly indicate the function of a control grid.

4. Describe an experimental arrangement for obtaining the characteristic curves of a triode valve and of calculating from them the amplification factor and the internal resistance of the triode. What do these constants signify?

5. Establish a mathematical relation between μ, r_p and g_m of a triode valve.

6. Explain with the help of suitable diagrams the characteristics of a tetrode and a pentode.

7. What are the functions of (a) screen grid and (b) supressor grid?

8. What is a beam-power tube?

9. If the anode current of a triode valve is changed from 8 to 14 m. amps the anode potential changes from 80 to 120 volts. Determine the valve constants if the changes above are obtained for a change of grid potential by 2 volts.

(*Ans.* r_p=6,666 ohms, $g_m=3\times10^{-3}$ mhos, $\mu=20$)

10. Calculate the plate resistance of a valve whose mutual conductance is 1.5 m. amps/volt and the amplification factor is 30. (*Ans.* 20 000 ohms)

CHAPTER 5

PHOTO ELECTRICITY

5.1 Introduction

The photo electric effect was first discovered by Hertz in 1887 who observed that air in the spark gap became a better conductor if the negative electrode was illuminated with ultraviolet light from an arc lamp. The effect was later studied by a number of research workers. Hallawachs noticed that the alkali metals give the largest amount of electrons and therefore they are best suited for photo emissive effects.

From their experiments it was evident that only negatively charged particles are emitted from a surface irradiated by UV radiations. From the measurement of the specific charge (e/m) of these particles Lenard concluded that they are identical with electrons. The particles thus emitted are generally called photo electrons and the effect is known as photo electricity.

The following two laws of photo electric emission are well established:

(i) Electrons emitted per second from a photo sensitive surface is directly proportional to the amount of light flux incident on it.

(ii) The maximum kinetic energy of electrons emitted from a photo sensitive surface is linearly related with the frequency of light flux but is independent of the amount of light flux.

5.2 Experimental Study

A typical arrangement for the general study of the photo electric phenomenon is shown in Fig. 5.1. Here K and A are two metallic plates

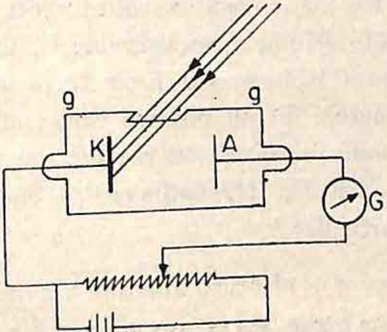


Fig. 5.1

fitted to the evacuated glass cylinder *gg* which has a window for the passage of incident light. With the help of a battery and a rehostat a potential difference is maintained between *K* and *A*, which can be altered as desired. A galvanometer *G* is connected in the circuit as shown.

When light from a quartz mercury arc lamp falls on *K*, the photo electrons are emitted by it. As a result current will flow in the circuit showing a deflection in the galvanometer. If monochromatic light of known wavelength be incident on *K*, the electrons emitted from the surface will be acted upon by the electric field between *K* and *A*. In the circuit if *A* is positive with respect to *K*, the electrons will be accelerated towards *A* and if *A* is negative they will be retarded. The current registered by *G* will be proportional to the number of electrons reaching at *A* per second. If this current (i) is plotted against the p.d. (V) applied between *K* and *A*, we get a curve as shown in Fig. 5.2(a). The figure shows that for all positive values of V, the current is constant and as *A* is made negative with respect to *K*, it decreases rapidly and reduces to zero at a certain value V_0. Only if the intensity of the incident beam is increased from I_1 to I_2, the value of i increases proportionately for all positive values of V, but gradually decreases as V is made negative and reaches the value $i=0$ for the same value of p.d., i.e. at V_0. This value of V_0 is known as the stopping potential for that particular λ.

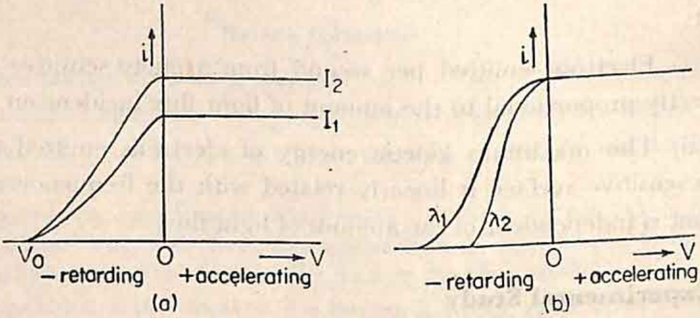


Fig. 5.2

Again if two beams of identical intensity but different λ's are used, then the nature of the curve will be as shown in Fig. 5.2(b). It is found from the figure that the stopping potential is different for different λ's.

5.3 Einstein's Photo Electric Equation

A satisfactory explanation of the laws of photo-electric emission was established by Einstein in 1905. The explanation was given on the basis of the quantum theory of light wherein he assumed that a beam of light consists of discrete 'bundles' of energy called 'quanta'. When light is made to fall on a metal surface some of this energy of a quantum is transferred to one of the unbound electrons within the metal causing to overcome the surface forces. If the applied energy is higher, the electrons are more readily released. According to the quantum theory given by Planck, the energy of each quantum is directly proportional to its frequency. If E is the quantum energy of a radiation of frequency ν then,

$$E=h\nu \qquad \ldots \qquad (5.1)$$

where h is a constant called Planck's constant and is equal to 6.62×10^{-27} ergs-second. If this energy is transferred to an electron within the metal, then the absorbing electron will get an energy equal to $h\nu$. Some part of this energy will be utilized in getting out an electron from the surface of the metal. If W_{min} represents the minimum energy necessary to release an electron from the metal, then the maximum kinetic energy that the electron can have, should be

$$\tfrac{1}{2}\, m_e\, v_{max}^2=h\nu-W_{min} \qquad \ldots \qquad (5.2)$$

where m_e is the mass of an electron and v_{max} is its maximum velocity.

Equation (5.2) above is the well-known Einstein's photo electric equation. W_{min} in the r.h.s. of equation (5.2) provides important informations regarding the origin of the photo-electrons. W_{min} is commonly known as the photo-electric work function.

The above equation of Einstein makes some important quantitative predictions:

(i) The maximum energy of emission is entirely determined by the frequency of the exciting radiation and is independent of its intensity.

(ii) The curve connecting the *K.E.* of the speediest electrons to the frequency of the exciting radiation is a straight line.

(iii) No electron will be able to eject unless the frequency ν of the incident light is sufficiently greater so that $h\nu$ is greater than or at least equal to W_{min}.

(iv) Lastly, it predicts a definite value for the maximum energy of ejection.

5.4 Threshold Frequency

After the discovery of the effect, it was observed that the photo electric emission occurs only when the incident radiation has a certain minimum frequency. That minimum frequency which causes emission is called threshold frequency. For different substances the threshold frequency is also different. It, however, usually lies in the ultra violet region. But in cases of alkali metals like Na, K etc., this frequency corresponds to that of the visible region of the spectrum.

If ν_t is the threshold frequency, then

$$h\nu_t = W_{min}$$

which gives

$$\nu_t = W_{min}/h \qquad \ldots \quad (5.3)$$

The wavelength corresponding to the threshold frequency is known as the threshold wavelength.

5.5 Classification of Photo Electric Phenomena

The phenomena may be broadly classified as follows:

(i) *Photo emissive effect*: It consists in the liberation of electrons from metal surface when exposed to light. The metal is then called a photo sensitive metal.

(ii) *Photo voltaic effect*: If the boundary surface between two substances in close contact is exposed to light, a p.d. is produced across the boundary. This is called photo voltaic effect.

(iii) *Photo conductive effect*: It consists in the change of resistance of semiconductors according to incident light.

5.6 Photo Electric Cells

Photo electric cells are devices with the help of which light energy can be converted into electrical energy and wherein the photo-electrons are the main agents for such conversion. Three different types of photo electric cells are there, viz. (i) *Photo emissive cells*, (ii) *Photo voltaic cells*, and (iii) *Photo conductive cells*.

5.6.1 Photo Emissive Cells

The cells consist of a photo sensitive surface from which electrons are emitted when light is made to fall on it. As a result a current will flow between this surface (called cathode) and a collecting plate (called anode) which is kept at a considerably high positive potential. Photo emissive cells are either of vacuum types or gas-filled types.

(a) *Vacuum Cells:* A vacuum type of emission cell is shown in Fig. 5.3. Here K is the cathode of large surface area coated with photosensitive material and A is the anode or the collecting plate. Both the cathode and the anode are mounted inside a high vacuum glass bulb and they are then connected with a battery terminals. The anode A is connected to the higher potential point while the cathode K is connected through a galvanometer G to the lower potential point of the battery. When light is allowed to fall on the cathode surface, photoelectrons are liberated and are repelled on to A from the cathode. As a matter of fact, a small current flows through the tube. With the increase of the p.d. between A and K, current increases at first and then a saturation stage is reached at a certain anode voltage. The current-voltage characteristic of a vacuum photo cell is shown in Fig. 5.4.

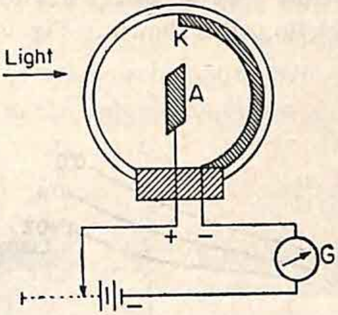


Fig. 5.3

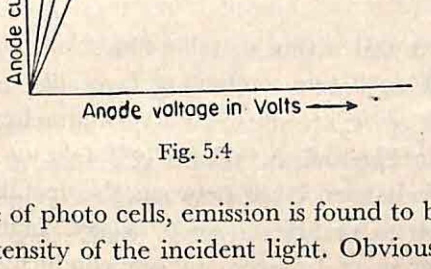


Fig. 5.4

In this type of photo cells, emission is found to be strictly proportional to the intensity of the incident light. Obviously, these are very quick and accurate in response.

(b) *Gas-filled Cells:* The output current of a gas-filled photo cells is considerably increased than in a vacuum photo cell by inserting an inert gas, like argon etc., at a low pressure. An increase of current and sensitivity is achieved here due to the production of ions by collision process in the neutral gas. The current-voltage characteristic of a gas-filled photo cell is shown in Fig. 5.5.

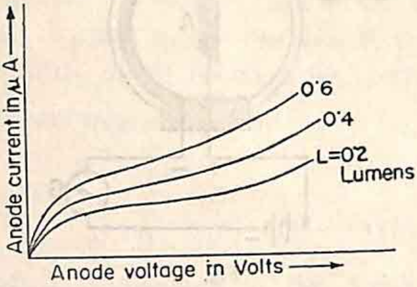


Fig. 5.5

Photo cell of this type is usually used for commercial purposes because of high sensitivity. But since there is a fluctuation of current even for a constant intensity beam, the gas-filled cells are seldom used for precision work.

5.6.2 Photo Voltaic Cells

Becquerel in 1839 discovered that when a pair of electrodes were immersed in an electrolyte and light was made to fall on one of the electrodes, a potential difference was created between them. This phenomenon is known as photo voltaic effect. Devices which exhibit this effect are called photo voltaic cells. Substances like selenium and silicon are mostly used for preparing photo voltaic cells. The recent forms of such cells are commonly known as barrier layer cells. Barrier layer cells are of two different types: (i) front-effect cell and (ii) back-effect cell.

In front-effect cell a thin metallic film *F* of silver, gold or platinum is deposited on a semiconducting layer like cuprous oxide or iron selenide. The whole arrangement is then attached to a metal base plate as shown in Fig. 5.6(a). When light falls on *F*, it penetrates easily and at the barrier layer between the metallic film and the semiconductor, photo electric emission occurs. Light further travels and at the barrier layer between the semiconductor and the metal base causes photo electric emission which is much less than in the previous case. As a result, the conventional current moves from the base to the metal film in the external circuit which is recognized by a metre *M*.

In the back-effect cell the light passes directly through the semi-conductor as shown in Fig. 5.6(b). Here electrons flow across the barrier layer from the semi-conductor to base plate and so conventional current flows in the opposite direction.

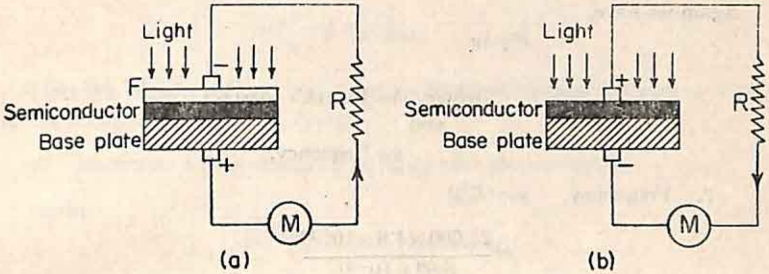


Fig. 5.6

Photo voltaic cells are used in photographic exposure metre and for operation of relays. Silicon cells, because of their better response in the infra-red region, are widely used in artificial satellites for conversion of solar energy into electrical energy. No separate battery is required to run photo voltaic cell.

5.6.3 Photo Conductive Cells

Substances like selenium, cadmium sulphide, cadmium selenide etc., decrease their resistances when light falls on them. The amount of this decrease, of course, depends on the intensity and colour of the incident light. So insertion of such a substance in the circuit and allowing light to fall on it will cause a change of electrical resistance. Hence there will be a variation of current in the circuit in steps with the variation of the intensity of the incident beam of light. This property is utilized in constructing photo conductive cells.

Photo conductive cells have a high sensitivity, low cost and long life. They can be used directly with a power supply of low voltage to operate a relay. These are used extensively in street lighting controls, door-openers, burglar alarm systems and also in modern television camera tubes.

Examples

1. In a discharge tube the p.d. between the cathode and anode surfaces is 25,000 volts. Express in electron-volts the energy of an electron inside the tube. If this electron is made to strike a target and if the whole energy is emitted as a photon then calculate its frequency.

The energy of an electron,

$$E = \text{p.d. between cathode and anode} \times 1 \text{ electronic charge}$$

$$= 25{,}000 \text{ electron-volts.}$$

Again we have,

$$E = h\nu$$

where h = Planck's constant
and
ν = frequency.

$$\therefore \text{ Frequency, } \quad \nu = (E/h)$$

$$= \frac{25{,}000 \times 1.6 \times 10^{-12}}{6.62 \times 10^{-27}}$$

$$(\because 1 \text{ electron-volt} = 1.6 \times 10^{-12} \text{ ergs})$$

$$= 0.6 \times 10^{19} \text{ c/s.}$$

2. An ultraviolet ray of wavelength 3,000 Å is made to fall on the surface of a metal which ejects an electron. If the work function of the metal is 2.28 electron-volts, find the velocity of the emitted electron. (Given, $m_e = 9.1 \times 10^{-28}$ gm.)

We have,

$$\tfrac{1}{2} m_e v_{max}^2 = h\nu - W_{min}$$

$$= h\,(c/\lambda) - W_{min}$$

where W_{min} = work function.

Now,

$$h = 6.62 \times 10^{-27} \text{ ergs-s.,}$$

$$c = 3 \times 10^{10} \text{ cm/s.}$$

$$\lambda = 3000 \text{ Å}$$

$$= 3000 \times 10^{-8} \text{ cm.}$$

$$W_{min} = 2.28 \text{ electron-volts}$$

$$= 2.28 \times 1.6 \times 10^{-12} \text{ ergs.}$$

So we get,

$$\tfrac{1}{2} m_e v_{max}^2 = \frac{6.62 \times 10^{-27} \times 3 \times 10^{10}}{3{,}000 \times 10^{-8}} - 2.28 \times 1.6 \times 10^{-12}$$

$$= 2.98 \times 10^{-12}$$

$$\therefore \qquad v_{max}=\sqrt{\frac{5.96\times10^{-12}}{9.1\times10^{-28}}}$$

$$=8.1\times10^{7}\text{ cm/s.}$$

3. When an ultra violet light of wavelength 3000Å falls on a metal surface, a retarding potential of 0.5 volts is applied to keep the most energetic electrons from reaching the collector. Calculate the work function.

We have, $\frac{1}{2}m_e v_{max}^2=h\nu-W_{min}$

or, $W_{min}=h\nu-\frac{1}{2}m_e v_{max}^2$

$$=h\frac{c}{\lambda}-\frac{1}{2}m_e v_{max}^2.$$

Here the increase of pot. energy of an electron passing through a retarding field of 0.5 volts=loss of its kin. energy.

∴ Maximum kinetic energy, $\frac{1}{2}m_e v_{max}^2=0.5$ electron-volts.

Again,

$$h=6.62\times10^{-27}\text{ ergs-second}$$

$$=\frac{6.62\times10^{-27}}{1.6\times10^{-12}}=4.13\times10^{-15}\text{ electron volts-second.}$$

$$c=3\times10^{10}\text{ cm/s.}$$

$$\lambda=3000\text{ Å}=3000\times10^{-8}\text{ cm.}$$

$$\therefore \qquad W_{min}=\frac{4.13\times10^{-15}\times3\times10^{10}}{3000\times10^{-8}}-0.5$$

$$=4.13-0.5=3.63\text{ electron-volts.}$$

Self-Test

Read each of the following and provide the appropriate words:

(a) Electrons emitted per second from a photosensitive surface is — proportional to the amount of light flux incident on it.

(b) The laws of photoelectric emission was established by — in 1905.

(c) W_{min} is commonly known as photoelectric —.

(d) The maximum energy of emission is independent of the frequency of the exciting radiation. (True/False)

(e) The minimum frequency which causes emission is called — frequency.

(f) Photoelectric cells are devices with the help of which — energy can be converted into — energy.

(g) In the back effect cell electrons flow across the barrier layer from the — to base plate.

(h) — cells are used in modern television camera tubes.

Review Questions

1. What are photo electrons?

2. What is meant by the photo electric effect? Give the laws of photo electric emission.

3. With necessary circuit diagram describe an arrangement for the general study of the photo electric phenomenon.

4. Explain Einstein's photo electric equation. What are the important quantitative predictions obtained from it?

5. What do you mean by threshold frequency and threshold wavelength?

6. What are the three different types of photo electric cells? Explain.

7. What are photo electric cells? Describe briefly the photo emissive, photo voltaic and photo conductive cells.

8. Discuss the utility of different photo electric cells.

9. A light of wavelength 0.43 micron is made to fall on the cathode surface of a photo tube. Find the maximum veloctity of electrons emitted from the photo cathode if its threshold wavelength is of 0.64 micron.

(*Ans.* 447×10^5 cm/s.)

CHAPTER 6

CATHODE RAY OSCILLOGRAPH

6.1 Introduction

Now-a-days perhaps all of us are familiar with at least one type of cathode ray tube used in the television picture tube known as kinescope. However, cathode ray tubes are of many types, sizes and shapes. The modern cathode ray tube is, in fact, an important modification of the Crookes tube discovered in 1879.

The C. R. tube is now widely used in laboratory to study the electric circuit phenomena. It is also extensively used as a viewing device for the reception of radar signals and television images. The C. R. tube is, in general, used in an assemblage of apparatus called a cathode ray oscillograph; the essential components of which are: (i) *cathode ray tube*, (ii) *deflection voltage amplifiers*, (iii) *power supplies* and (iv) *time base circuit.*

6.2 Construction

A cathode ray tube, as shown in Fig. 6.1, has the following main components:

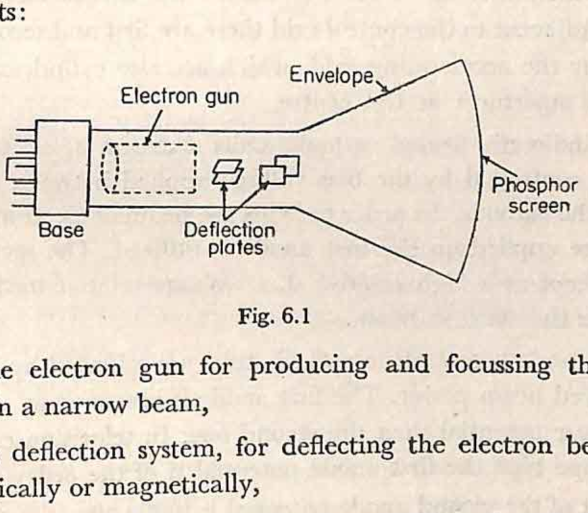


Fig. 6.1

(i) the electron gun for producing and focussing the emitted electrons in a narrow beam,

(ii) a deflection system, for deflecting the electron beam either electrostatically or magnetically,

and (iii) a fluorescent screen, upon which the electron beam impinges to create a visible light spot.

A tube base is there to which connections from the elements inside the tube are made. The components of a C. R. tube are mounted carefully inside a highly evacuated glass envelope.

6.3 Electron Gun

In an electrostatically focussed C. R. tube, as illustrated in Fig. 6.2, the electron gun consists of (a) an *indirectly heated cathode*, (b) a *control grid*, (c) an *accelerating electrode*, (d) a *first focussing anode* and (e) a *second*, or *final accelerating anode.*

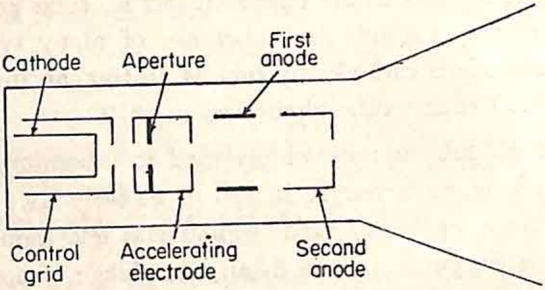


Fig. 6.2

The cylindrical cathode is usually coated with barium and strontium oxides for providing a plentiful supply of electrons. By a tungsten heater wire this cathode is indirectly heated. The control grid is a cylinder with a tiny aperture at its centre and is kept enveloping the cathode. Adjacent to the control grid there are first and second anodes, followed by the accelerating grid, which are also cylindrical in shape with small apertures at the centre.

The indirectly heated cathode emits a stream of electrons whose density is controlled by the bias voltage applied between the control grid and the cathode. In order to focus the beam of electrons properly, the voltage applied on the first anode is utilized. The second anode which is kept at a high positive d. c. voltage relative to the cathode, accelerates the electron beam.

The anode potentials in a C. R. tube are adjusted by considering the required beam power. The first anode is always kept at an appreciably lower potential than the second one. In television camera tube of iconscope type the first anode potential is of the order of 300 volts while that of the second anode potential is 1000 volts.

6.4 Fluorescent Screen

If the beam of electrons coming from the electron gun is not deflected it would form a luminous spot of light at the centre of the fluorescent screen. Though the control grid is usually used to control the intensity of this spot, but it is also dependent on the fluorescent material. The fluorescent material coated inside the tube is termed as phosphor. Some commonly used phosphors are: zinc silicate, zinc oxide, zinc sulphide etc.

6.5 Deflection Sensitivity

The beam of electrons in a C. R. tube are deflected by two different means: (i) *electrostatically* and (ii) *magnetically*.

Electrostatic deflection—The electrostatic deflection sensitivity is the amount of deflection of electron spot produced on the screen when a voltage of one volt from a d. c. source is applied to the deflection plates. The unit of deflection sensitivity is then expressed in inch/volt or mm/volt.

The geometry of the electrostatic deflection system is shown in Fig. 6.3. In the figure, V_d is the potential applied betwen two plates

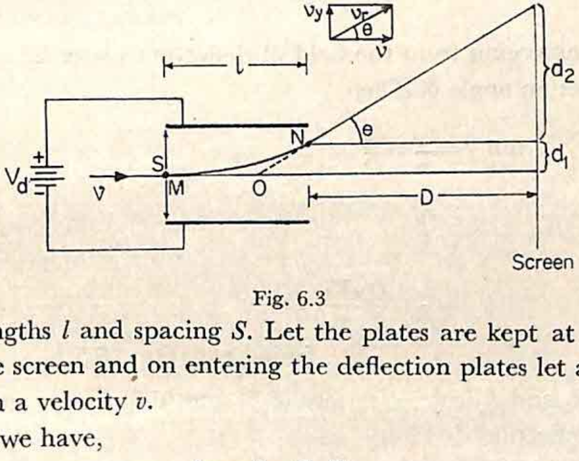


Fig. 6.3

each of lengths l and spacing S. Let the plates are kept at a distance D from the screen and on entering the deflection plates let an electron moves with a velocity v.

Then we have,

$$\frac{1}{2} m_e v^2 = Q_e V_a \qquad \ldots \qquad (6.1)$$

where, m_e=mass of an electron, Q_e=its charge and V_a=final a node voltage.

From equation (6.1) we get,

$$v^2 = \frac{2Q_e}{m_e} V_a \qquad \ldots \qquad (6.2)$$

The electrons during its movement are attracted towards the positive plate with a force F

where $$F = \frac{Q_e V_d}{S} \qquad \ldots \qquad (6.3)$$

If f is the acceleration produced by the force F then

$$f=\frac{Q_e . V_d}{S . m_e} \qquad \ldots \qquad (6.4)$$

Since an electron moves with a velocity v, the time required to traverse the fields of the plate is l/v. Let v_y be the upward velocity attained in this time interval l/v, so that,

$$v_y=\frac{l}{v} . f=\frac{l}{v} . \frac{Q_e . V_d}{S . m_e} \qquad \ldots \qquad (6.5)$$

From the point of entrance to the point of leaving, i.e. from M to N, the electrons move in a curved path. Let d_1 be the vertical displacement during this period. Then,

$$\begin{aligned} d_1 &= \tfrac{1}{2} f \left(\frac{l}{v}\right)^2 \\ &= \tfrac{1}{2} \frac{Q_e . V_d}{S . m_e} \frac{l^2}{v^2} \qquad \ldots \qquad (6.6) \end{aligned}$$

After emerging from the field of deflection plates let the electron beam makes an angle θ. Then,

$$\tan \theta=\frac{v_y}{v}=\frac{d_2}{D}$$

i.e.,

$$\begin{aligned} d_2 &= \frac{v_y}{v} . D \\ &= \frac{l}{v^2} . \frac{Q_e V_d}{S . m_e} . D \qquad \ldots \qquad (6.7) \end{aligned}$$

[using equation (6.5)]

Knowing d_1 and d_2 from equations (6.6) and (6.7) we can now calculate the total deflection d. Thus,

$$\begin{aligned} d &= d_1+d_2 \\ &= \frac{Q_e V_d}{S m_e} \frac{l}{v^2}\left(\frac{l}{2}+D\right) \\ &= \frac{Q_e V_d}{S . m_e} \frac{l}{v^2} . L \qquad \left(\text{where } L=\frac{l}{2}+D\right) \\ &= \frac{Q_e . V_d}{S . m_e} . \frac{l . m_e}{2 Q_e . V_a} . L \end{aligned}$$

[substituting the value of v^2 from equation (6.2)]

i.e.,

$$d=\frac{l L}{2 S} . \frac{V_d}{V_a} \qquad \ldots \qquad (6.8)$$

Now by definition,

$$\text{deflection sensitivity, } S_e=\frac{d}{V_d}$$

$$=lL/2S\,V_a \qquad \dots \qquad (6.9)$$

For a given C. R. tube, l, L and S are fixed and so varying the voltage applied to the plates, V_d, or the final anode voltage V_a, one may alter the deflection spot d. It is also seen from equation (6.9) that the deflection sensitivity is inversely proportional to the final anode voltage.

Magnetostatic deflection—The magnetic deflection sensitivity is defined as the amount of deflection of electron spot produced when one milliampere current flows through the deflection coil. The unit of deflection sensitivity is then expressed in inch/mA or mm/mA. In this system the magnetic field is produced by passing current through the coil, as in Fig. 6.4, whose axis is kept normal to the direction of the electron beam.

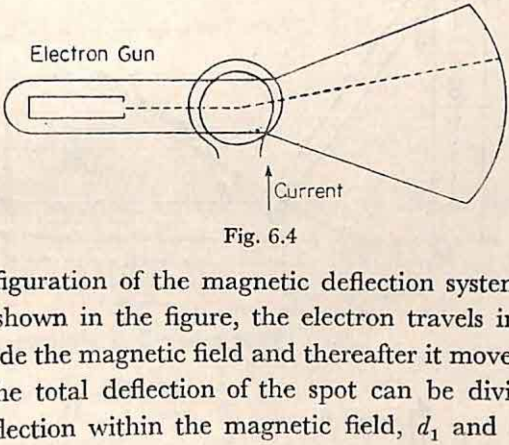


Fig. 6.4

The configuration of the magnetic deflection system is shown in Fig. 6.5. As shown in the figure, the electron travels in an arc *MN* of a circle inside the magnetic field and thereafter it moves in a straight line. Thus, the total deflection of the spot can be divided into two parts: (i) deflection within the magnetic field, d_1 and (ii) deflection outside the field, d_2.

Let in the direction of electron beam, θ be the angular change in passing through the magnetic field and also let the electron moves in a circle of radius r inside the field, so that,

$$d_1=r-r\cos\theta$$

$$=r-r\sqrt{1-\sin^2\theta}$$

$$=r-r\sqrt{1-\frac{l^2}{r^2}} \quad \left(\because \sin\theta=\frac{l}{r}\right)$$

$$=r\left(1-\sqrt{1-\frac{l^2}{r^2}}\right)$$

or, $$\frac{d_1}{r}=\frac{r-\sqrt{r^2-l^2}}{r}$$

or, $$r-d_1=\sqrt{r^2-l^2}$$

or, $$r^2-2rd_1+d_1^2=r^2-l^2$$

or, $$(2r-d_1)d_1=l^2 \qquad \ldots \quad (6.10)$$

In equation (6.10), we may neglect d_1^2 comparing $2rd_1$ and hence we have,

$$2rd_1=l^2$$

i.e., $$d_1=\frac{l^2}{2r} \qquad \ldots \quad (6.11)$$

Again, from Fig. 6.5 we get,

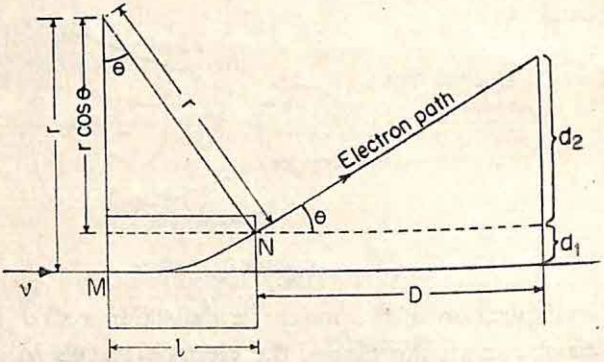


Fig. 6.5

$$\frac{d_2}{D}=\tan\theta$$

or, $$d_2=D\tan\theta$$

$$=D\,\frac{\sin\theta}{\cos\theta}$$

$$=D\,\frac{\sin\theta}{\sqrt{(1-\sin^2\theta)}}$$

$$=D\,\frac{l/r}{\sqrt{1-\frac{l^2}{r^2}}}$$

$$\text{or, } d_2=\frac{Dl}{\sqrt{(r^2-l^2)}} \qquad \ldots \qquad (6.12)$$

Therefore the total displacement,

$$d=d_1+d_2$$

$$=\frac{l^2}{2r}+\frac{Dl}{\sqrt{(r^2-l^2)}} \qquad \ldots \qquad (6.13)$$

If the deflection coil is sufficiently short, so that l is small in comparison to r, we can write from equation (6.13),

$$d=Dl/r \qquad \ldots \qquad (6.14)$$

Now the centrifugal force of an electron is given by $m_e v^2/r$, which is equal to the force F exerted on the electron by the magnetic field. Since in the case under consideration, the angle between the direction of magnetic flux and direction of motion of electrons is 90°, we have,

$$F=H\,Q_e\,v\sin 90°$$

$$=H\,Q_e\,v \qquad \ldots \qquad (6.15)$$

where H is the magnetic flux density.

Now, as discussed above, we may write,

$$\frac{m_e v^2}{r}=HQ_e\,v$$

$$\text{i.e.,} \quad r=\frac{m_e v}{HQ_e} \qquad \ldots \qquad (6.16)$$

Substituting the value of r from equation (6.16) in equation (6.14) we get,

$$d=Dl.\,\frac{HQ_e}{m_e v} \qquad \ldots \qquad (6.17)$$

So that, the magnetic deflection sensitivity,

$$S_m=\frac{d}{H}=Dl.\,\frac{Q_e}{m_e}\,.\,\frac{1}{v} \qquad \ldots \qquad (6.18)$$

Using equation (6.2), this may be expressed alternatively in terms of final anode potential V_a as,

$$S_m=Dl\,\frac{Q_e}{m_e}\sqrt{\frac{m_e}{2Q_eV_a}}$$

$$=Dl\sqrt{\frac{Q_e}{2m_eV_a}} \qquad \ldots \qquad (6.19)$$

Equation (6.19) shows that the deflection sensitivity is directly proportional to the square root of the ratio of charge to mass of an electron but inversely proportional to the square root of the final anode potential.

6.6 Power Supplies

In a C. R. tube the final anode potential is generally of the order of 1000 to 2000 volts. In television and radar circuits, however, much higher anode potentials are required and so the power supply in such cases must be designed accordingly.

In practice the final anode is often kept at the earth potential while a negative voltage is applied to the other electrode of the C. R. tube. This avoids the danger of electrical shock which may come if the final anode is kept at a high positive voltage as this terminal is frequently required to be handled during the study of waveforms etc. using a C. R. O.

6.7 Time Base or Sweep Circuits

On the front panel of a cathode ray oscillograph there are various d. c. voltage controls which are named as: (i) *focus control*, (ii) *intensity control*, (iii) *horizontal position control* and (iv) *vertical position control.* Using these controls the beam is first focussed to a spot and then it can be placed at any desired position on the screen.

In addition to all these d. c. voltage controls, a source of sweep voltage is internally provided. The waveform of this sweep generator output is of the shape of saw-tooth, as shown in Fig. 6.6, and so this voltage is termed as saw-tooth voltage. As seen from the figure, the voltage during each cycle increases linearly with time upto t_i and then falls to zero in a shorter time t_f.

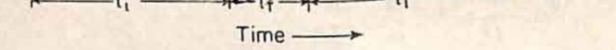


Fig. 6.6

Using a switch the saw-tooth generator may be connected to the horizontal deflecting plates. In the most common form, since the deflection of the spot in the horizontal direction (or vertical or sometimes circular) is proportional to time, it is called time base and the retracing time t_f is known as the flyback time. Some common types of time base circuits are: (i) Neon time base, (ii) Pucklle's hard valve time base, (iii) Thyratron time base etc. Out of these the neon time base is discussed in the next subsection.

6.7.1 Neon Time Base

The property of neon tube is applied in a neon time base circuit. It has been found that a neon tube conducts at a definite potential called the striking potential. But if that potential is gradually reduced, a stage is reached called extinguishing potential, when the conduction by ionisation ceases. This behaviour is important in the operation of neon time base. A basic neon time base circuit is shown in Fig. 6.7.

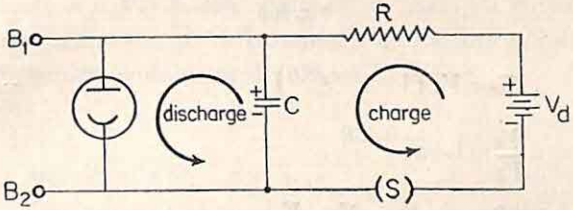


Fig. 6.7

In the figure, a voltage source V_d is connected with a high resistance R and a capacitor C. When the battery circuit is made on, the voltage V_c across the capacitor increases exponentially with time by a relation

$$V_c = V_d \left(1 - \varepsilon^{-t/CR}\right) \qquad (6.20)$$

where t is the time in seconds.

Neglecting smaller terms we can write,

$$V_c = \frac{V_d t}{CR} \qquad \dots \qquad (6.21)$$

Equation (6.21) shows that the voltage across the condenser V_c is approximately proportional to the time. The value of V_c depends on the time constant CR of the charging circuit. When the value of CR is low, the rate of charging becomes more rapid. At the striking potential neon tube starts to conduct and its resistance decreases to a very small value, say r ohms. The condenser C then discharges exponentially through the neon tube with a time constant Cr. The charging and discharging curves of a condenser is shown in Fig. 6.8. Since the value of r is small, the discharge of condenser becomes more rapid.

The time period T of a neon time base potential is the sum of time of charge t_i and time of discharge (flyback interval) t_f. Referring to Fig. 6.8, the extinguishing potential V_e at time t_i is given by,

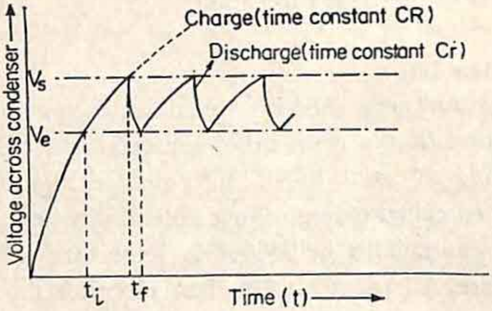


Fig. 6.8

$$V_e = V_d\left(1 - \varepsilon^{-t_i/CR}\right) \quad \ldots \quad (6.22)$$

or, $$\frac{V_e}{V_d} = 1 - \varepsilon^{-t_i/CR}$$

or, $$\varepsilon^{-t_i/CR} = 1 - \frac{V_e}{V_d} = \frac{V_d - V_e}{V_d} \quad \ldots \quad (6.23)$$

and the striking potential V_s at time t_f is,

$$V_s = V_d\left(1 - \varepsilon^{-t_f/CR}\right) \quad \ldots \quad (6.24)$$

or, $$\varepsilon^{-t_f/CR} = 1 - \frac{V_s}{V_d} = \frac{V_d - V_s}{V_d} \quad \ldots \quad (6.25)$$

Dividing equation (6.23) by equation (6.25), we get

$$\varepsilon^{(t_f - t_i)/CR} = \frac{V_d - V_e}{V_d - V_s}$$

or, $$\frac{t_i}{CR} = \log_\varepsilon \frac{V_d - V_e}{V_d - V_s}$$

Since t_f is small compared to t_i, we can write $t_i \simeq T$, the periodic time.

Hence, $$T = CR \log_\varepsilon \frac{V_d - V_e}{V_d - V_s} \quad \ldots \quad (6.26)$$

or the frequency, $f = \frac{1}{T}$

$$= \frac{1}{CR \log_\varepsilon \dfrac{V_d - V_e}{V_d - V_s}} \quad \ldots \quad (6.27)$$

It may be noted here that the sweep-voltage curve departs considerably from linearity in a neon time base circuit. This is achieved by utilizing the constant current property of a pentode.

6.8 Frequency and Phase Measurements

If suitable alternating voltages are applied to the two sets of deflection plates of a C. R. O. various patterns may be obtained on the screen in the form of closed loop or straight line. These figures are known as 'Lissajous Figures'. If v_x and v_y are the two instantaneous voltages applied to the x and y plates we can write,

$$v_x = V_x \sin \omega_x t \qquad \ldots \qquad (6.28)$$

$$\text{and} \quad v_y = V_y \sin (\omega_y t + a) \qquad \ldots \qquad (6.29)$$

where V_x and V_y are the voltage amplitudes; ω_x, ω_y are the angular frequencies and a is the phase angle for v_y voltage. By adjusting all these parameters the so-called 'Lissajous Figures' are obtained on the screen. Some typical conditions are discussed below.

CONDITION 1:

When $\omega_x = \omega_y$ and $a = 0$

then equations (6.28) and (6.29) reduces to,

$$v_y = \frac{V_y}{V_x} v_x \qquad \ldots \qquad (6.30)$$

which is the equation of a straight line passing through the origin as shown in Fig. 6.9(a).

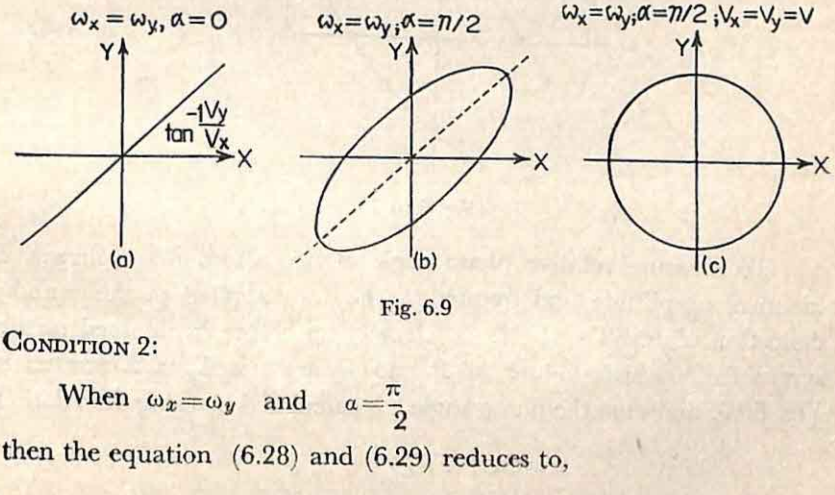


Fig. 6.9

CONDITION 2:

When $\omega_x = \omega_y$ and $a = \frac{\pi}{2}$

then the equation (6.28) and (6.29) reduces to,

$$\frac{v_x^2}{V_x^2}+\frac{v_y^2}{V_y^2}=1 \qquad \ldots \qquad (6.31)$$

which is the equation of an ellipse as shown in Fig. 6.9(b).

CONDITION 3:

When $\omega_x=\omega_y$, $\alpha=\frac{\pi}{2}$ and $V_x=V_y=V$

then equations (6.28) and (6.29) reduces to,

$$v_x^2+v_y^2=V^2 \qquad \ldots \qquad (6.32)$$

which is the equation of a circle as shown in Fig. 6.9(c).

In order to measure the frequencies of an alternating voltage, it is applied to one set of deflection plates while at the other set sinusoidal voltage is applied from a variable frequency standard oscillator which is properly calibrated. The oscillator is allowed to work for some time to get a stabilized temperature and then the frequency of this oscillator is altered until a single loop stationary pattern is obtained. Now, the frequency of the oscillator voltage is noted from the calibrated dial of the oscillator which is equal to the frequency of the alternating voltage applied.

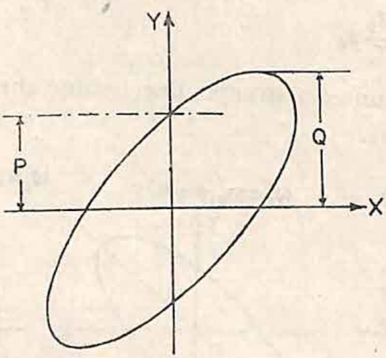


Fig. 6.10

To measure relative phase angle of two alternating voltages of identical amplitude and frequency, they are applied to the x and y deflection plates of a C. R. O. Usually an ellipse is obtained on the screen from which values of P and Q are noted, as illustrated in Fig. 6.10, and then the phase angle α is calculated by using the relation,

$$\alpha=\sin^{-1}(P/Q) \qquad \ldots \qquad (6.33)$$

Examples

1. In a cathode ray oscillograph, a pair of deflecting plates are 2.0 cms long and are separated by a distance of 0.5 cms. If the distance of the fluorescent screen from the centres of the plates is 36 cms, find the deflection sensitivity for a final anode voltage of 1000 volts.

We have,

Deflection sensitivity,

$$S_e = \frac{lL}{2SV_a}$$

Here

$$l = 2.0 \text{ cms}$$

$$S = 0.5 \text{ cms}$$

$$L = 36 \text{ cms}$$

and

$$V_a = 1000 \text{ volts}$$

$$\therefore \quad S_e = \frac{2 \times 36}{2 \times 0.5 \times 1000} \text{ cm/volts}$$

$$= 0.072 \text{ cm/volts.}$$

2. In a cathode ray oscillograph, the spacing of the plates is 0.5 cms, the length of the deflecting plates is 2.0 cms and the distance of the screen from the centre of the plates is 12 cms. Find the value of the displacement produced by a deflecting voltage of 30 volts (Given that the final anode voltage = 2000 volts).

We have,

$$\frac{d}{V_d} = \frac{lL}{2SV_a}$$

or

$$d = \frac{lL}{2SV_a} . V_d$$

Here

$$l = 2.0 \text{ cms}$$

$$S = 0.5 \text{ cms}$$

$$L = 12 \text{ cms}$$

$$V_d = 30 \text{ volts}$$

$$V_a = 2000 \text{ volts}$$

$$\therefore \quad d = \frac{2 \times 12 \times 30}{2 \times 0.5 \times 2000} \text{ cms} = 0.36 \text{ cms.}$$

3. A cathode ray tube has a magnetic deflection field of flux density 10^{-4} weber/sq. metres for a 3-cm distance along the axis of the tube. The final anode potential is 800 volts. Calculate the deflection of electron spot when the distance from the screen to the end of the coil is 20 cms.

We have,

$$\frac{d}{H}=Dl\sqrt{\frac{Q_e}{2m_eV_a}}$$

i.e.,

$$d=D\,l\,H\sqrt{\frac{Q_e}{2m_eV_a}}$$

Here,

$$D=20 \text{ cms}$$
$$=20\times10^{-2} \text{ metres}$$
$$l=3 \text{ cms}$$
$$=3\times10^{-2} \text{ metres}$$
$$H=10^{-4} \text{ weber/sq. metre}$$
$$\frac{Q_e}{m_e}=1.76\times10^{11} \text{ coulombs/kilogram}$$
$$V_a=800 \text{ volts}$$

∴ the deflection,

$$d=\frac{20\times10^{-2}\times3\times10^{-2}\times10^{-4}\sqrt{1.76\times10^{11}}}{\sqrt{(2\times800)}} \text{ metres}$$
$$=6.29\times10^{-3} \text{ metres}$$
$$=0.629 \text{ cms.}$$

Self-Test

Read each of the following and provide the appropriate words:

(a) The deflection system in a cathode ray tube is used for deflecting the electron beam either magnetostatically or —.

(b) The cylindrical cathode is usually coated with — and — oxides for providing a plentiful supply of electrons.

(c) The first anode is always kept at an appreciable — potential than the second one. (lower/higher)

(d) The unit of electrostatic deflection sensitivity is expressed in —.

(e) Magnetic deflection sensitivity is the amount of deflection of electron spot when one — current flows through the deflection coil.

(f) In a C. R. tube the final — potential is generally of the order of 1000 to 2000 volts.

(g) The waveform of the sweep generator output is of the shape of —.

Review Questions

1. What are the uses of a cathode-ray oscillograph? What are its essential components?

2. Describe briefly the construction of a cathode-ray tube.

3. Obtain expressions for the electrostatic and magnetic deflection sensitivities of a C. R. tube.

4. What is a sweep circuit? Explain its function.

5. Define 'time base' and 'flyback time'. Give names of some common time base circuits.

6. Discuss briefly with necessary diagrams the operation of a neon time base circuit.

7. Neglecting the flyback period, obtain an expression for the frequency of a neon time base.

8. What are 'Lissajous Figures'? How are these obtained on the screen?

9. How can the frequency and phase be determined experimentally?

10. In a cathode-ray oscillograph, the pair of deflecting plates are 2 cms long and separated by a distance of 0.5 cms. The distance of the screen from the centre of the plate is 9 cms. Calculate the deflection sensitivity in cm/volt for an anode voltage of 500 volts. (*Ans.* 0.036 cm./volt)

11. A cathode ray tube has a magnetic deflection field of flux density 10.35×10^{-5} weber/sq. metre and the distance from the end of the field to the screen is 24 cms. If the length of the field along the axis is 4 cms, calculate the final anode voltage in volts to produce a deflection of 1.2 cms on the screen. (*Ans.* 600 volts)

CHAPTER 7

RECTIFIERS AND FILTERS

7.1 Introduction

Power companies generally supply a.c. power because it can be easily generated and also economical to transmit. On the other hand, d.c. supply usually serves the power requirements for various electronic devices. This demands a rectification of a.c. into d.c. voltages and currents. A rectifier must provide a substantially one-way path for the flow of electric current. That is a rectifier changes a.c. into pulsating d.c. by eliminating the negative half cycle. This is called a unidirectional characteristic or unilateral conduction. The diode is admirably suited for rectification as it permits current to flow in one direction only. The diode used for such purpose may be (i) electron tubes of the vacuum or gas-filled type, (ii) metallic type like copper oxide or selinium rectifiers, and (iii) crystals or semiconductors made of germanium or silicon. Now-a-days selenium rectifiers or crystal diodes are widely used in various electronic circuits as no filament supply is required there and so they have become increasingly popular in the field of radio and television receivers, in particular.

Because of the pulsations in its amplitudes the output voltage obtained after rectification is not suitable enough for d.c. supply. These pulsations are smoothed out properly by using filter circuit consisting of choke coils and capacitors.

7.2 Rectifiers

Rectifiers may be broadly put into two categories depending on the period of conduction. These are (a) *half wave rectifier* and (b) *full wave rectifier*.

7.2.1 Half wave rectifier

A half wave rectifier (one diode) converts the applied alternating voltage to a pulsating voltage using half cycle of the applied voltage. That is the conduction takes place during one half cycle only. The circuit of half wave rectifier using vacuum diode is shown in Fig. 7.1.

In the figure, the input is an a.c. voltage applied across the series connected diode and the load resistance R_L. During the positive half cycle the anode is positive with respect to cathode and the current flows in the circuit while during the negative half cycle since the anode is negative with respect to cathode no current flows. Now, as because the variation of current will follow the variation of input voltage, the output voltage across the load resistor R_L should follow the positive half cycle. The nature of input and output waveforms are shown in Fig. 7.2. It is interesting to note that the output voltage is now a pulsating voltage instead of the a.c. voltage applied at the input.

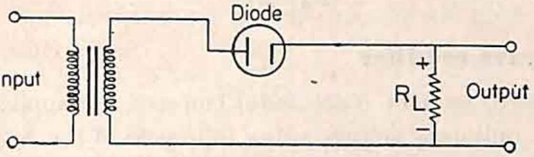


Fig. 7.1

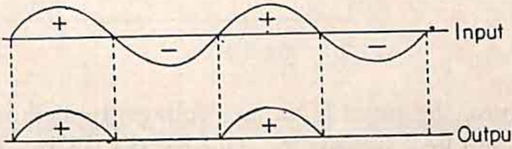


Fig. 7.2

Fig. 7.1, shown before, is a circuit for an ideal rectifier. In an idealized rectifier, however, there is a definite constant slope in the conduction region. An idealized circuit diagram for a half wave rectifier is shown in Fig. 7.3. In this figure, a resistor R_a is connected in series with R_L so that the total impedance in the circuit is (R_a+R_L). If i be the flow of current and $E_m \sin \omega t$ be the sinusoidal input voltage then the output voltage E_{out} is given by,

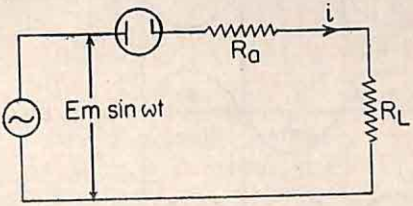


Fig. 7.3

$$E_{out}=i \cdot R_L \quad \cdots \quad (7.1)$$

and the value of maximum current

$$I_m = \frac{E_m}{(R_a + R_L)} \quad \ldots \quad (7.2)$$

7.2.2 Full wave rectifier

A full wave rectifier (two diode) converts the applied alternating voltage to a pulsating voltage using full cycle of the applied voltage. That is the conduction takes place by the one rectifier element during one half and by the other element during the other half cycle. A circuit of full wave rectifier using vacuum duo-diode is shown in Fig. 7.4.

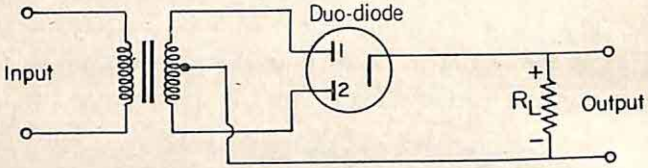


Fig. 7.4

In the figure, the input is an a.c. voltage applied across the two element diode and load resistor R_L. During the positive half period of the applied a.c. voltage one diode conducts and the other not while during the other half cycle of the a.c. voltage the second diode only conducts. Let e_1 and e_2 be the nature of the output voltages for the first and the second diode as shown in Fig. 7.5. Then obviously the

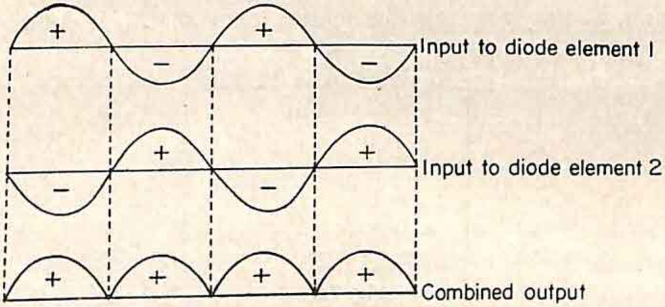


Fig. 7.5

combined output voltage (e_1+e_2) of both diode elements will be of the form as shown. It is to be noted that the output voltage obtained is pulsating in nature.

An idealized circuit diagram for a full wave rectifier is shown in Fig. 7.6. The total current flowing in the circuit will be the sum of the individual currents i_1 and i_2

i.e., $$i=i_1+i_2 \qquad \ldots \qquad (7.3)$$

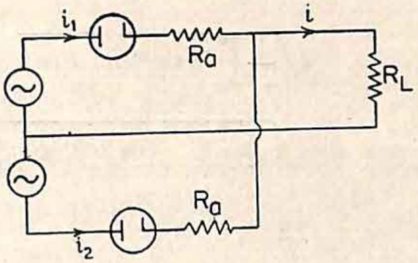


Fig. 7.6

The value of maximum current is again given by,

$$I_m=\frac{E_m}{(R_a+R_L)} \qquad \ldots \qquad (7.4)$$

7.2.3 Expressions for Currents and Voltages of the Two Rectifiers

(i) D.C. or average value of current

For a half wave (H.W.) rectifier this may be expressed as,

$$(I_{dc})_{\text{H. W.}}=\frac{1}{2\pi}\int_0^{2\pi} i\,.\,d(\omega t)$$

$$=\frac{1}{2\pi}\int_0^{\pi} I_m \sin\omega t\,.\,d(\omega t)+\frac{1}{2\pi}\int_{\pi}^{2\pi} 0\,.\,d\,(\omega t)$$

$$=\frac{I_m}{2\pi}\Big[-\cos\omega t\Big]_0^{\pi}=\frac{I_m}{\pi} \qquad \ldots \qquad (7.5)$$

For a full wave (F.W.) rectifier,

$$(I_{dc})_{\text{F. W.}}=\frac{1}{\pi}\int_0^{\pi} i\,.\,d(\omega t)$$

$$=\frac{2I_m}{\pi}$$

$$=\frac{2E_m}{\pi(R_a+R_L)} \text{ [substituting the value of } I_m\text{]} \quad (7.6)$$

(ii) R.M.S. value of current

For a half wave rectifier this may be expressed as,

$$(I_{rms})_{\text{H. W.}}=\sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2\, d(\omega t)}$$

$$=\sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_m^2 \sin^2 \omega t\, .\, d(\omega t)}$$

$$=\sqrt{\frac{I_m^2}{4\pi}\int_0^{\pi} (1-\cos 2\omega t)\, d(\omega t)}$$

$$=\frac{I_m}{2} \qquad \dots \qquad (7.7)$$

For a full wave rectifier,

$$(I_{rms})_{\text{F.W.}} = \sqrt{\frac{1}{\pi}\int_0^{\pi} i^2\, .\, d(\omega t)}$$

$$= \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi} \sin^2 \omega t\, .\, d(\omega t)}$$

$$=\frac{I_m}{\sqrt{2}} \qquad \dots \qquad (7.8)$$

(iii) D.C. or average voltage across the load

For a half wave rectifier this may be expressed as,

$$(E_{dc})_{\text{H.W.}} =(I_{dc})_{\text{H.W.}}\, .\, R_L$$

$$=\frac{E_m}{\pi(R_a+R_L)}.R_L$$

$$=\frac{E_m}{\pi\left((1+\frac{R_a}{R_L}\right)} \qquad \dots \qquad (7.9)$$

For a full wave rectifier,

$$(E_{dc})_{\text{F.W.}} = (I_{dc})_{\text{F.W.}}\, .\, R_L$$

$$=\frac{E_m}{\left(1+\frac{R_a}{R_L}\right)}\cdot \frac{2}{\pi} \qquad \dots \qquad (7.10)$$

(iv) R.M.S. value of the voltage across the load

For a half wave rectifier this may be expressed as,

$$(E_{rms})_{\text{H.W.}} = (I_{rms})_{\text{H.W.}} \cdot R_L$$

$$= \frac{I_m}{2} \cdot R_L$$

$$= \frac{E_m}{2\left(1 + \frac{R_a}{R_L}\right)} \qquad \ldots \qquad (7.11)$$

For a full wave rectifier,

$$(E_{rms})_{\text{F.W.}} = (I_{rms})_{\text{F.W.}} \cdot R_L$$

$$= \frac{I_m}{\sqrt{2}} \cdot R_L$$

$$= \frac{E_m}{\sqrt{2}\left(1 + \frac{R_a}{R_L}\right)} \qquad \ldots \qquad (7.12)$$

7.2.4 Ripple factor

We have found that the rectified output is unidirectional in nature. But because of the continuous changes in amplitudes or pulsations the current is not a direct (d.c.) one, rather these pulsations contain both d.c. and a.c. components.

The ripple factor, denoted by γ, may be defined as,

$$\gamma = \frac{\text{effective value of the a.c. components of current (or voltage)}}{\text{d.c. value of current (or voltage)}}$$

$$= \frac{I_{ac}}{I_{dc}}$$

$$= \sqrt{\frac{I^2_{rms} - I^2_{dc}}{I^2_{dc}}} \quad (\because \quad I_{rms} = \sqrt{I^2_{ac} + I^2_{dc}})$$

$$= \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

$$= \sqrt{F^2 - 1} \qquad \ldots \qquad (7.13)$$

where, $F = \frac{I_{rms}}{I_{dc}}$, is called the form factor.

For a half wave rectifier,

$$(F)_{\text{H.W.}}=\frac{I_m/2}{I_m/\pi}=\frac{\pi}{2}=1.57$$

$$\therefore\quad (\gamma)_{\text{H.W.}}=\sqrt{(1.57)^2-1}=1.21 \qquad \ldots \qquad (7.14)$$

and for a full wave rectifier,

$$(F)_{\text{F.W.}}=\frac{I_m/\sqrt{2}}{2I_m/\pi}=\frac{\pi}{2\sqrt{2}}=1.11$$

$$\therefore\quad (\gamma)_{\text{F.W.}}=\sqrt{(1.11)^2-1}=0.48 \qquad \ldots \qquad (2.15)$$

It thus appears that the ripple factor for a full wave rectifier is small in comparison to half wave rectifier.

7.2.5 Efficiency

The efficiency of the rectifier, denoted by η, may be defined as,

$$\eta=\frac{\text{d.c. output power}}{\text{a.c. input power}}$$

$$=\frac{P_{dc}}{P_{ac}} \qquad \ldots \qquad (7.16)$$

Of the input power, a portion P_a is dissipated at the anode of the rectifier tube and the remaining portion P_L is dissipated in the load resistor. So we can write,

$$P_{ac}=P_a+P_L$$

$$=I^2_{rms}\,(R_a+R_L) \qquad \ldots \qquad (7.17)$$

Again the useful power output P_{dc} developed across the load R_L may be expressed as,

$$P_{dc}=I^2_{dc}\,.\,R_L \qquad \ldots \qquad (7.18)$$

Using equations (7.17) and (7.18) we can write,

$$\eta=\frac{I^2_{dc}\,.\,R_L}{I^2_{rms}\,(R_a+R_L)}$$

$$=\left(\frac{I_{dc}}{I_{rms}}\right)^2\cdot\frac{1}{1+\dfrac{R_a}{R_L}} \qquad \ldots \qquad (7.19)$$

For a half wave rectifier,

$$\left(\frac{I_{dc}}{I_{rms}}\right)_{\text{H.W}} = \frac{I_m/\pi}{I_m/2}$$

$$= \frac{2}{\pi}$$

$$\therefore \quad (\eta)_{\text{H.W.}} = \left(\frac{2}{\pi}\right)^2 \cdot \frac{1}{1+\frac{R_a}{R_L}}$$

$$= \frac{0.406}{1+\frac{R_a}{R_L}} \quad \ldots \quad (7.20)$$

Thus the % efficiency for a half wave rectifier

$$= \frac{40.6}{1+\frac{R_a}{R_L}} \text{ per cent} \quad \ldots \quad (7.21)$$

For a full wave rectifier,

$$\left(\frac{I_{dc}}{I_{rms}}\right)_{\text{F.W.}} = \frac{2I_m/\pi}{I_m/\sqrt{2}}$$

$$= \frac{2\sqrt{2}}{\pi}$$

$$\therefore \quad (\eta)_{\text{F.W.}} = \left(\frac{2\sqrt{2}}{\pi}\right)^2 \cdot \frac{1}{1+\frac{R_a}{R_L}}$$

$$= \frac{0.812}{1+\frac{R_a}{R_L}} \quad \ldots \quad (7.22)$$

Thus the % efficiency for a full wave rectifier,

$$= \frac{81.2}{1+\frac{R_a}{R_L}} \text{ per cent} \quad \ldots \quad (7.23)$$

7.2.6 Comparative study

We may compare a half wave rectifier with a full wave rectifier by considering the following important points.

(i) Ripple factor of a half wave rectifier is greater than that of a full wave rectifier.

(ii) Rectifier efficiency of a full wave rectifier is double than that of a half wave rectifier.

(iii) Half wave rectifier has a low transformer efficiency and a low output voltage than that of a full wave rectifier.

(iv) In half wave rectification current through the secondary of a transformer flows in the same direction while in full wave rectification equal currents flow in the opposite direction through the centre-tapped secondary.

(v) Half wave rectifier has low cost in comparison to a full wave rectifier.

7.3 Filter

The output voltage obtained by using a rectifier circuit includes ripple which must be minimized to use it as a d.c. source. The required smoothing action is achieved by filter networks. Choke, capacitor and resistor are usually filter elements.

7.3.1 Choke input filter

A circuit diagram for a choke input filter is shown in Fig. 7.7. Since the first component of the filter circuit is a choke coil connected in series with the rectifier output, it is called a choke input filter.

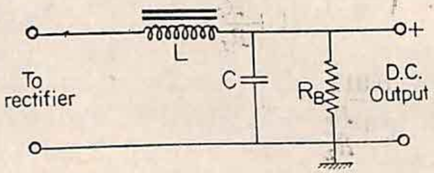


Fig. 7.7

The direct current coming from the rectifier easily passes through the choke coil L but the a.c. pulsations (i.e., ripples) are opposed by it. Further fluctuations of the current after passing through L are largely bypassed at the output of the filter consisting of the shunt capacitor C and a resistor R_B, known as a bleeder resistor. The bleeder has the following important functions: (i) It helps to maintain a constant output voltage by drawing a minimum current at all times. (ii) When the receiver tubes or other loads in the circuit are heating up, the bleeder resistor maintains a minimum load across the rectifier. Without the resistor R_B, there would be an initial high voltage surge as soon as the rectifier is turned on which might damage the circuit. (iii) After the rectifier has been turned off, the bleeder discharges the capacitors and thus helps to prevent dangerous shocks.

The nature of the filtered waveform is shown in Fig. 7.8 in addition to the waveform obtained at the rectifier output. Note that a small ripple is still present in the filter output. To improve the smoothing action several identical filter sections are often used instead of only one. It is also to be noted that the d.c. output here has not attained the peak value of pulsation. This happens because the choke coil prevents the capacitor to charge at the peak value when a load current is drawn. However, beyond the initial drop the filtered output voltage changes very little with the changes of the load current. The choke input filter circuit thus provides a good voltage regulation.

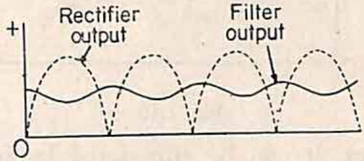


Fig. 7.8

7.3.2 Capacitor input filter

A circuit diagram for a capacitor input filter is shown in Fig. 7.9. Since the first component of the filter circuit is a shunt capacitor connected across the rectifier, it is called a capacitor input filter.

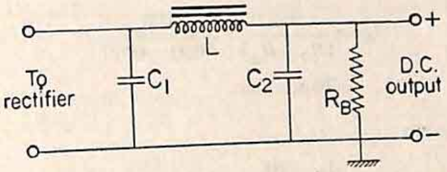


Fig. 7.9

The output voltage obtained from the rectifier circuit, first charges the capacitor C_1 to the peak value of pulsations which, however, discharges slowly through the choke coil and the load. The remaining fluctuations of rectifier output current after passing through C_1 are opposed by the choke coil L and thereafter largely bypassed at the output of the filter consisting of a capacitor C_2 and a bleeder resistor R_B.

The nature of the filtered waveform is shown in Fig. 7.10 in addition to the waveform obtained at the rectifier output. If a small ripple is still present, it can be eliminated by using identical filter circuits in series. It is to be noted that the d.c. output voltage remains substantially near the peak value. This happens because the capacitor C_1 tends to hold the charge at the peak value between successive pulses. For the same a.c. input the output voltage thus attains a comparatively higher value than that of a choke input filter. However, in the present case the output voltage rapidly falls with an increase of load current and so the voltage regulation is considerably poor.

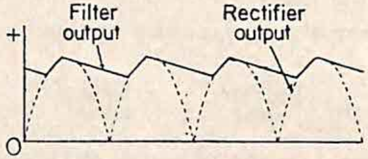


Fig. 7.10

Examples

1. In a half wave vacuum tube rectifier without filter the load resistance is 4 K. Voltage applied to the diode has amplitude of 100 volts with a frequency of 50 c.p.s. The diode has idealized characteristic in series with a resistance of 1 K. Find the (i) peak, R.M.S. and average values of current; (ii) A.C. input power and D.C. output power and (iii) ripple factor.

Here, $E_m=100$ volts, $R_a=1K=1000\ \Omega$, $R_L=4\ K=4000\ \Omega$

(i) Peak current,

$$I_m=\frac{E_m}{(R_a+R_L)}=\frac{100}{1000+4000}$$
$$=20 \text{ mamps.}$$

R.M.S. current,

$$I_{rms}=\frac{I_m}{2}=\frac{20}{2}=10 \text{ mamps.}$$

Average current,

$$I_{dc}=\frac{I_m}{\pi}=6.36 \text{ mamps.}$$

(ii) A.C. input power,

$$P_{ac}=I^2_{rms}\,(R_a+R_L)$$
$$=(10\times10^{-3})^2\times5000$$
$$=0.5 \text{ watts}$$

D.C. output power,

$$P_{dc}=I^2_{dc}\times R_L$$
$$=(6.36\times10^{-3})^2\times4000$$
$$=(6.36)^2\times4\times10^{-3}$$
$$=0.162 \text{ watts (approx.)}.$$

(iii) Ripple factor,

$$\gamma=\frac{I_{ac}}{I_{dc}}=\sqrt{\frac{I^2_{rms}-I^2_{dc}}{I^2_{dc}}}=\sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2-1}$$

$$=\sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2-1}=\sqrt{\left(\frac{\pi}{2}\right)^2-1}=1.21.$$

2. A voltage 240 sin 2π $50t$ is applied to a full wave vacuum tube rectifier without filter. Each diode has idealized characteristic having slope for a resistance of $1K$. If the load resistance is $4K$ find the rectifier efficiency and the peak value of current.

Here $E_m=240$ volts, $R_a=1K=1000$ ohms, $R_L=4K=4000$ ohms.

(i) Rectifier efficiency, $\eta=\dfrac{P_{dc}}{P_{ac}}=\dfrac{I^2_{dc}R_L}{I^2_{rms}\,(R_a+R_L)}=\dfrac{0.812}{1+\dfrac{R_a}{R_L}}$

$$=\frac{0.812}{1+\frac{1}{4}}=64.96\%.$$

(ii) Peak current $=\dfrac{E_m}{R_a+R_L}=\dfrac{240}{1000+4000}$

$$=\frac{240}{5000}=48 \text{ mamps.}$$

Self-Test

Read each of the following and provide the appropriate words:

(a) — supply usually serves the power requirements for various electronic devices.

(b) Output voltage obtained after rectification are smoothed out by using — circuits.

(c) A — rectifier converts the applied alternating voltage to a pulsating voltage using half cycle of the applied voltage.

(d) Ripple factor may be defined as the ratio of effective value of the — components of current to the — value of current.

(e) The rectifier efficiency may be defined as the ratio of — output power to the — input power.

(f) In half wave rectification current through the secondary of a transformer flows in the same direction. (True/False)

(g) In full wave rectification equal currents flow in the — direction through the centre-tapped secondary.

(h) The bleeder resistor maintains a — load across the rectifier. (minimum/maximum).

Review Questions

1. What is a rectifier? Why rectification is required?

2. Draw half wave and full wave rectifier circuits. Briefly explain their operations.

3. Discuss how current is rectified in a rectifier.

4. Draw the circuit diagram of a full wave vacuum tube rectifier using a centre-tapped power transformer and clearly explain how current is rectified in it.

5. Find expressions for average and r.m.s. currents and voltages of a half wave and a full wave rectifier.

6. What is meant by (a) ripple factor, (b) form factor and (iii) efficiency of a rectifier. Obtain expressions for them.

7. Show that the maximum efficiency of a full wave rectifier is twice the value obtained in a half wave rectifier.

8. Make a comparative study of a half wave and a full wave rectifier.

9. Why it is necessary to smooth out the ripples from the rectifier output? How this can be done?

10. Briefly discuss with necessary diagrams the following: (a) Choke input filter, (b) Capacitor input filter.

11. In a half wave vacuum tube rectifier without filter the load resistance is $6K$, the r.m.s. value of input a.c. voltage is 300 volts and the slope of diode corresponds to 1 K. Calculate the (i) peak, average and r.m.s. output voltages, (ii) peak, average and r.m.s. currents, (iii) d.c. power output and total power input and (iv) ripple factor.

(*Ans.* (i) 363 V, 116 V, 182 V, (ii) 60.6 mamps, 19.3 mamps, 30.3 mamps, (iii) 2.234 watts, 6.425 watts, (iv) 1.21)

12. A voltage of effective value 240 volts with a frequency 50 Hz is applied to each diode of a full wave vacuum tube rectifier. Diodes have idealized characteristics with slope corresponding to a resistance of 800 ohms. Load is a resistance of 4000 ohms. Supposing no filter to be used, find (i) the average and r.m.s. values of current, (ii) total power input and (iii) form factor.

(*Ans.* (i) 31.84 mamps, 35.36 mamps., (ii) 6.001 watts, (iii) 1.11)

CHAPTER 8

AMPLIFIERS

8.1 Introduction

The function of an amplifier is to increase the level of the current, voltage or power at its output. The amount of this increase is called the amplification or gain of the amplifier. It is called a voltage amplifier if the output voltage becomes greater than the input voltage. A power amplifier, on the other hand, is used to supply power (i.e., voltage times current) to the output or load circuit. If a number of amplifiers are connected in series so that the output of one becomes input to the next then the early stages build up the voltage to a high level while the last stage builds up the power to a level suitable for operating a speaker or other similar devices. This amplifier is known as a cascade amplifier. The present chapter deals with the common forms of both voltage and power amplifiers using vacuum tubes.

8.2 Classification of Amplifiers

Amplifiers may be classified in a variety of ways as discussed below:

(a) According to the type of load used amplifiers are classified as: (i) *untuned amplifiers* and (ii) *tuned amplifiers.*

Untuned amplifiers are again divided into two groups. These are audio frequency (upto about 15 kHz) and video frequency amplifiers (upto a few MHz).

The tuned amplifiers, also referred to as radio frequency amplifiers, are used to amplify an electrical signal containing a radio frequency (a frequency above 30 kHz).

(b) According to the number of stages and methods of coupling amplifiers are classified as: (i) *single stage amplifiers* and (ii) *cascade amplifiers.*

A single stage amplifier is suitable for cases where small amplification is necessary while in a cascade amplifier considerable amount of gain is achieved. Depending on the method of coupling cascade amplifiers may again be divided as: Resistance-Capacitance (R-C) coupled amplifier, Transformer coupled amplifier, Direct coupled or D.C. amplifier and L.C. coupled amplifier.

(c) According to the choice of the operating point of the vacuum tube amplifiers are classified as: (i) *Class A*, (ii) *Class AB*, (iii) *Class B* and (iv) *Class C amplifiers*.

In a class A amplifier the grid bias and the input signal are so adjusted that the plate current flows during the entire cycle of the input signal. A class AB amplifier is designed such that the plate current flows for more than half but less than the complete cycle of the input voltage. A class B amplifier is designed to have its grid bias almost equal to the cut off voltage so that the plate current flows for half the a.c. cycle while in a class C amplifier the plate current flows over less than the half period of the input signal. In all the above classes of amplifiers a subscript 1 is added to letter or letters to indicate that the grid current does not flow during any part of the input cycle (e.g., class A_1) while a subscript 2 is given to indicate that the grid current flows during part of the input cycle (e.g., class A_2).

8.3 Single Stage Voltage Amplifier (Untuned Class A_1)

The basic circuit of a single stage untuned class A_1 amplifier using a triode is shown in Fig. 8.1. The resistor R_g between the grid and the cathode is the grid leak resistor and Z_L is the load impedance which is, in general, complex. If an alternating voltage is applied between the grid and the cathode of the tube, an amplified voltage is obtained across Z_L and thus it acts as a voltage amplifier.

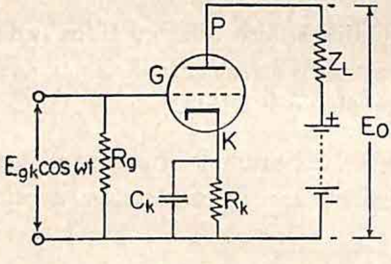


Fig. 8.1

Let us assume that R_g is very large and also C_k is so large in comparison to the cathode resistor R_k that its reactance may be neglected. Then we can draw, as shown in Fig. 8.2, the a.c. equivalent circuit of the amplifier valid for linear class A_1 operation. It should be noted that the equivalent circuit may be drawn by (i) eliminating all d.c. voltage and current sources, (ii) considering only a.c. or incremental values of currents and voltages and (iii) replacing the tube by a current or voltage generator.

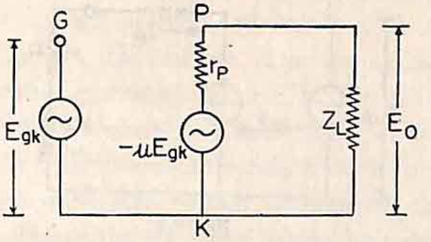


Fig. 8.2

Let us consider a source supplying grid potential of r.m.s. value E_{gk} so that the equivalent voltage generator generates a voltage of value μE_{gk}. The total impedance in the plate circuit then becomes $(r_P+\mathbf{Z}_L)$, where r_P is the series resistance.

The r.m.s. value of the a.c. plate current $\mathbf{I}_p$ is given by,

$$\mathbf{I}_P=\frac{\mu \mathbf{E}_{gk}}{(r_P+\mathbf{Z}_L)} \quad \ldots \quad (8.1)$$

This current $\mathbf{I}_P$ flowing through the load impedance $\mathbf{Z}_L$ produces the output voltage between the plate and the cathode. Let it be denoted by $\mathbf{E}_0$, where,

$$\mathbf{E}_0=-\mathbf{I}_P\mathbf{Z}_L$$

$$=-\frac{\mu \mathbf{E}_{gk}}{(r_P+\mathbf{Z}_L)}\cdot \mathbf{Z}_L \quad \text{[(from equation (8.1)]} \quad (8.2)$$

$$\therefore \quad \text{complex voltage gain, } \mathbf{A}=\frac{\text{complex output voltage}}{\text{complex input voltage}}$$

$$=\frac{\mathbf{E}_0}{\mathbf{E}_{gk}}=-\frac{\mu \mathbf{Z}_L}{(r_p+\mathbf{Z}_L)} \quad \ldots \quad (8.3)$$

In equation (8.3), $\mathbf{A}$ is a complex quantity since the load impedance $\mathbf{Z}_L$ is a complex factor, in general, containing both resistive and reactive parts. We may consider three special cases as below.

Case 1: $\mathbf{Z}_L$ *complex inductive*

The a.c. equivalent circuit of a single stage amplifier is shown in Fig. 8.3, where the load impedance $\mathbf{Z}_L$ is expressed as,

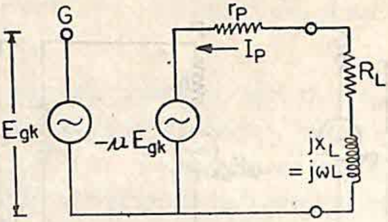


Fig. 8.3

$$\mathbf{Z}_L = R_L + jX_L$$
$$= R_L + j\omega L$$

Then, $\mathbf{I}_p = \dfrac{\mu \mathbf{E}_{gk}}{r_p + R_L + j\omega L}$

and $\mathbf{E}_o = -\dfrac{\mu \mathbf{E}_{gk}(R_L + j\omega L)}{(r_p + R_L) + j\omega L}$

$$\therefore \text{ voltage gain } \mathbf{A} = \frac{\mathbf{E}_o}{\mathbf{E}_{gk}} = -\frac{\mu(R_L + j\omega L)}{(r_p + R_L) + j\omega L} \quad \ldots \quad (8.4)$$

Or we can write,

$$A = \frac{\mu\sqrt{R_L^2 + \omega^2 L^2}}{\sqrt{(r_p + R_L)^2 + \omega^2 L^2}}\left(180^\circ + \tan^{-1}\frac{\omega L}{R_L} - \tan^{-1}\frac{\omega L}{r_p + R_L}\right)$$
$$= G\angle\theta \quad \ldots \quad (8.5)$$

where G is the magnitude of the gain and θ is the phase angle.

Here the phase angle $\theta = 180^\circ + \tan^{-1}\dfrac{\omega L}{R_L} - \tan^{-1}\dfrac{\omega L}{r_p + R_L}$.

It is interesting to consider here the same problem in the case of a pentode amplifier and also its advantages over a triode. Since the dynamic plate resistance r_p of a pentode is very large in equation (8.3), Z_L in the denominator may be neglected compared with r_p. Therefore the expression for voltage gain of a pentode may be written as,

$$\mathbf{A} = -\frac{\mu \mathbf{Z}_L}{r_p}$$
$$= -g_m \mathbf{Z}_L \quad \left(\because \frac{\mu}{r_p} = g_m\right) \quad \ldots \quad (8.6)$$

This means that the voltage gain in a pentode may be increased simply by increasing the load impedance.

In the construction of a pentode, as we know, a suppressor grid is inserted between the screen grid and the plate, which is usually connected directly to the cathode. The suppressor is thus kept at a substantial negative potential relative to the plate to eliminate the effects of secondary emission. As a matter of fact, with increasing plate voltage the plate current rises smoothly from zero upto the maximum value for each control grid voltage. Moreover, the presence of suppressor grid increases the shielding action between the plate and the control grid and therefore reduces the grid to plate capacitance. As a result, the amplification of a pentode becomes extremely high even 1,000–2,000 for specially designed tubes. In spite of such a high μ, pentode as an amplifier is very stable in operation because of its low capacitance between the control grid and the plate.

Besides, pentodes are also used as a wideband amplifier or video amplifier in Radar and Television circuits. For amplifying pulses, it becomes necessary to amplify over a very wide frequency range. The pentode is then designed specially, keeping spacing between the control grid and the cathode small and also by keeping the pitch of the control grid wires small.

Case 2: *Z_L purely resistive*

We have, $\mathbf{Z}_L=(R_L+jX_L)$

For pure resistance load, $X_L=0$

$$\therefore\ Z_L=R_L$$

$$\text{Then,}\quad \mathbf{I}_p=\frac{\mu\mathbf{E}_{gk}}{(r_p+R_L)}$$

$$\text{and } \mathbf{E}_o=-\mathbf{I}_P\,.\,R_L=-\frac{\mu\mathbf{E}_{gk}R_L}{(r_p+R_L)}$$

$$\therefore\ \text{voltage gain,}\quad \mathbf{A}=\frac{\mathbf{E}_o}{\mathbf{E}_{gk}}$$

$$=-\frac{\mu R_L}{(r_p+R_L)} \qquad \dots \qquad (8.7)$$

or, $$A = \frac{\mu R_L}{r_p + R_L} (\cos 180° + j \sin 180°)$$

$$= \left| \frac{\mu\ R_L}{r_p + R_L} \right| \angle 180°$$

$$= G \angle \theta \qquad \ldots \qquad (8.8)$$

where, G is the magnitude of the gain and θ is the phase shift of the plate voltage with respect to the grid voltage.

Case 3: *Z_L purely inductive*

In this case, $R_L = 0$

$$\therefore \qquad Z_L = 0 + jX_L = 0 + j.\omega L$$

Then, $$\mathbf{I}_p = \frac{\mu \mathbf{E}_{gk}}{r_p + j\omega L}$$

and $$\mathbf{E}_o = -\mathbf{I}_p . j\omega L$$

$$= -\frac{\mu \mathbf{E}_{gk}}{r_p + j\omega L} \cdot j\omega L$$

$$\therefore \text{ voltage gain} = \frac{\mathbf{E}_o}{\mathbf{E}_{gk}} = -\frac{\mu}{1 + \frac{r_p}{j\omega L}} \qquad \ldots \qquad (8.9)$$

$$= \frac{\mu}{\sqrt{1 + \left(\frac{r_p}{\omega L}\right)^2}} \left(270° - \tan^{-1} \frac{\omega L}{r_p}\right)$$

$$= G \angle \theta \qquad \ldots \qquad (8.10)$$

where the phase angle is $\left(270° - \tan^{-1} \frac{\omega L}{r_p}\right)$.

8.4 Distortion in Amplifiers

The amplified output in an ideal amplifier is the enlarged version of the input signal. But in practice, a difference is noticed always between the output and input waveforms. The amplifier is then said to have a distortion. The three main types of distortions are the amplitude distortion, frequency distortion and phase distortion.

Amplitude distortion—The distortion is caused by non-linear operation, such as plate current cut off and grid current flow. This distortion results when harmonic frequencies not present in the input signal appear in the output.

Frequency distortion—This distortion is caused by the amplifier coupling elements when singals of different frequencies are amplified separately. In general, both amplitude and frequency distortions may be present simultaneously in an amplifier.

Phase distortion—This distortion is due to the unequal delay of different audio frequencies by phase shifts in the amplifier coupling elements.

8.5 Resistance-Capacitance Coupled Amplifier

The resistance-capacitance coupled amplifier, as the name implies, consists of a load resistance R_L and a coupling capacitor C_c as shown in Fig. 8.4. Besides coupling, the capacitor C_c also serves the purpose of blocking the d.c. from the plate of one stage to the grid of the next. In the figure, the cathode is provided with self-bias arrangement by the use of a resistance R_k and a capacitor C_k while the grid leak resistor R_g is used to enable the cathode bias voltage to reach the grid. The presence of interelectrode capacitances C_g between the grid and the cathode and C_p between the plate and the cathode are also drawn in the figure. Between the stages, these capacitors form part of the coupling network. A constant voltage and a constant current generator form of a.c. equivalent circuits for R.C. coupled amplifiers are shown in Fig. 8.5(a) and (b) respectively. To obtain general expressions for voltage gain of this amplifier the entire audio frequency range is divided into low, middle and high frequency ranges. The analysis, as given below, is based on the equivalent circuit of Fig. 8.5(b). In the figure, the a.c. voltage source E_{gk} is connected between the grid and the cathode of the first tube so that a constant current

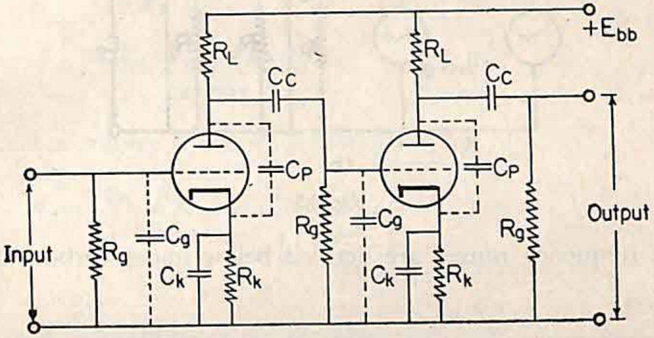
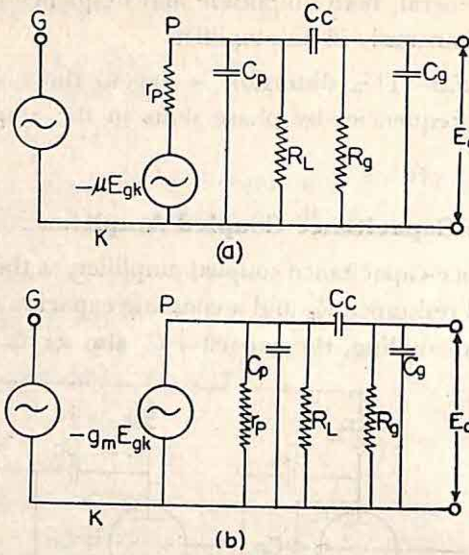


Fig. 8.4

generator delivers a current $g_m E_{gk}$, where E_{gk} is the a.c. voltage at the input of the second tube. Three expressions for voltage gain for different frequency ranges are derived below under certain approximations.



(a)

(b)

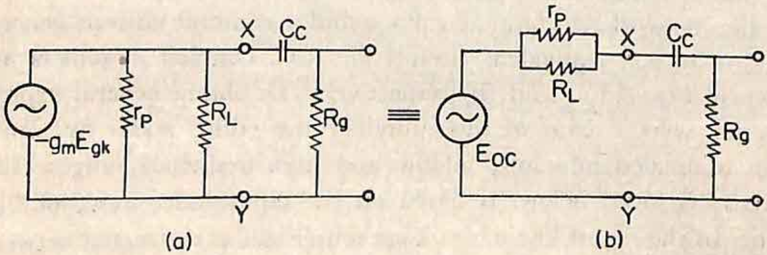
Fig. 8.5

(i) At low frequency

At the low frequencies, the interelectrode capacitances may be neglected but the coupling capacitor C_c must be retained as shown in the equivalent circuit of Fig. 8.6(a).

Applying Thevenin's theorem, the open circuit voltage $\mathbf{E}_{oc}$ across the terminals X–Y is given by,

$$\mathbf{E}_{oc} = -g_m \mathbf{E}_{gk} \frac{r_p R_L}{r_p + R_L} \quad \dots \quad (8.11)$$



(a)

(b)

Fig. 8.6

Again the internal impedance Z_{in} is found by replacing the energy sources by the source impedances. Then we can write,

$$Z_{in}=\frac{r_pR_L}{r_p+R_L} \qquad \ldots \qquad (8.12)$$

i.e., Z_{in} is the resistance of the parallel combination of r_p and R_L as shown in the modified circuit of Fig. 8.6(b).

Let Z'_{in} represents the total impedance in this modified circuit. Then,

$$\begin{aligned} Z'_{in} &= Z_{in}+R_g \\ &= \frac{r_pR_L}{r_p+R_L}+R_g \\ &= \frac{r_pR_L+r_pR_g+R_LR_g}{r_p+R_L} \qquad \ldots \qquad (8.13) \end{aligned}$$

Output a.c. voltage across R_g is then given by

$$\mathbf{E}_o=\frac{\mathbf{E}_{oc}\,.\,R_g}{Z'_{in}-jX_c}=\frac{\mathbf{E}_{oc}\,.\,R_g}{Z'_{in}\left(1-\frac{jX_c}{Z'_{in}}\right)} \qquad \ldots \qquad (8.14)$$

where,

$$\begin{aligned} X_c &= \text{reactance of the coupling capacitor, } C_c \\ &= \frac{1}{\omega C_c} \end{aligned}$$

Substituting the value of $\mathbf{E}_{oc}$ from equation (8.11) in equation (8.14) we get,

$$\mathbf{E}_o=-\frac{g_m\mathbf{E}_{gk}\frac{r_pR_LR_g}{(r_p+R_L)Z'_{in}}}{1-\frac{jX_c}{Z'_{in}}} \qquad \ldots \qquad (8.15)$$

Let R_{plg} represents the equivalent resistance of the parallel combinations of r_p, R_L and R_g, so that

$$\begin{aligned} \frac{1}{R_{plg}} &= \frac{1}{r_p}+\frac{1}{R_L}+\frac{1}{R_g} \\ &= \frac{r_pR_L+r_pR_g+R_LR_9}{r_pR_LR_g} \end{aligned}$$

$$\text{or,}\quad R_{plg}=\frac{r_pR_LR_g}{r_pR_L+r_pR_g+R_LR_g}$$

$$=\frac{r_pR_LR_g}{(r_p+R_L)}\times\frac{(r_p+R_L)}{r_pR_L+r_pR_g+R_LR_g}$$

$$=\frac{r_pR_LR_g}{(r_p+R_L)Z'_{in}} \qquad \ldots \quad (8.16)$$

[by using equation (8.13)]

$$\therefore\quad E_o=-\frac{g_m\mathbf{E}_{gk}R_{plg}}{1-\dfrac{jX_c}{Z'_{in}}} \qquad \ldots \quad (8.17)$$

Hence the complex voltage gain in the low frequency range $\mathbf{A}_{lf}$ is given by,

$$\mathbf{A}_{lf}=\frac{\mathbf{E}_o}{\mathbf{E}_{gk}}=-\frac{g_mR_{plg}}{1-\dfrac{jX_c}{Z'_{in}}}$$

$$=\frac{g_mR_{plg}}{\sqrt{1+\dfrac{X_c^2}{Z'^2_{in}}}}\left(180^\circ+\tan^{-1}\frac{X_c}{Z'_{in}}\right)$$

$$=G_{lf}\ \theta_{lf} \qquad \ldots \quad (8.18)$$

where,

the magnitude of voltage gain, $G_{lf}=\dfrac{g_mR_{plg}}{\sqrt{1+\dfrac{X_c^2}{Z'^2_{in}}}}$

and phase shift $\theta_{lf}=\left(180^\circ+\tan^{-1}\dfrac{X_c}{Z'^2_{in}}\right)$

(ii) At middle frequency

At the middle frequencies the capacitors C_c, C_p and C_g may be neglected as shown in the equivalent circuit of Fig. 8.7.

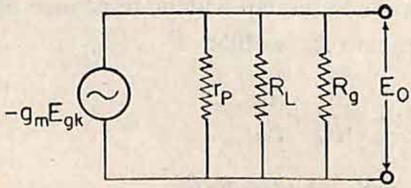


Fig. 8.7

Now, since the current $g_m E_{gk}$ flowing through R_{plg} produces the output voltage $\mathbf{E}_o$, we can write,

$$\mathbf{E}_o = -g_m \mathbf{E}_{gk} \cdot R_{plg}$$

$\therefore$ the mid frequency gain

$$\begin{aligned} \mathbf{A}_{mf} &= \frac{\mathbf{E}_o}{\mathbf{E}_{gk}} \\ &= -g_m R_{plg} \\ &= g_m R_{plg} \angle 180^\circ \\ &= G_{mf}\ \theta_{mf} \end{aligned} \quad \ldots \quad (8.19)$$

where,

$$G_{mf} = g_m R_{plg}$$

and

$$\theta_{mf} = 180^\circ.$$

(iii) At high frequency

At high frequencies, the coupling capacitor C_c is negligible but the interelectrode capacitances C_p and C_g have to be retained as shown in Fig. 8.8. In the figure, the effective capacitance of the parallel combinations of C_p and C_g may be denoted by C_i

i.e., $C_i = C_p + C_q$.

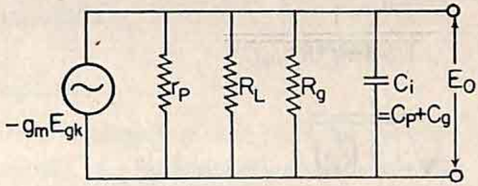


Fig. 8.8

Then, the output voltage $\mathbf{E}_o$ is given by,

$$\mathbf{E}_o = -g_m \mathbf{E}_{gk} \frac{(R_{plg}/j\omega C_i)}{R_{plg} + \left(\frac{1}{j\omega C_i}\right)}$$

$$= -g_m \mathbf{E}_{gk} \frac{R_{plg}}{j\omega C_i \cdot R_{plg} + 1}$$

∴ the high frequency gain,

$$\mathbf{A}_{hf}=\frac{\mathbf{E}_o}{\mathbf{E}_{gk}}=-\frac{g_m \,.\, R_{plg}}{j\omega C_i \,.\, R_{plg}+1}$$

$$=-\frac{g_m R_{plg}}{1+j\dfrac{R_{plg}}{X_i}} \quad \left(\text{where, } X_i=\frac{1}{\omega C_i}\right)$$

$$=\frac{g_m \,.\, R_{plg}}{\sqrt{1+\left(\dfrac{R_{plg}}{X_i}\right)^2}}\left(180^\circ-\tan^{-1}\frac{R_{plg}}{X_i}\right)$$

$$=G_{hf}\,\theta_{hf} \qquad \ldots \qquad (8.20)$$

where,

$$G_{hf}=\frac{g_m \,.\, R_{plg}}{\sqrt{1+\left(\dfrac{R_{plg}}{X_i}\right)^2}}$$

and $$\theta_{hf}=\left(180^\circ-\tan^{-1}\frac{R_{plg}}{X_i}\right)$$

From equations (8.19) and (8.20) we can now calculate the ratio of high to mid-frequency gain of the amplifier. Thus,

$$\frac{G_{hf}}{G_{mf}}=\frac{1}{\sqrt{1+\left(\dfrac{R_{plg}}{X_i}\right)^2}}$$

$$=\frac{1}{\sqrt{1+4\pi^2 f^2 R^2_{plg} C_i^2}}$$

$$=\frac{1}{\sqrt{1+\left(\dfrac{f}{f_2}\right)^2}} \qquad \ldots \qquad (8.21)$$

where, $f_2=\dfrac{1}{2\pi\, R_{plg} C_i}$, is called the upper half power frequency.

Similarly we can write,

$$\theta_{hf}=180^\circ-\tan^{-1}\frac{f}{f_2} \qquad \ldots \qquad (8.22)$$

At $f=f_2$,

$$\theta_{hf}=180^\circ-\tan^{-1} 1$$

$$=135^\circ.$$

8.6 Transformer Coupled Amplifier

In a transformer coupled amplifier, as shown in Fig. 8.9, a so-called interstage transformer is used to couple two amplifier tubes.

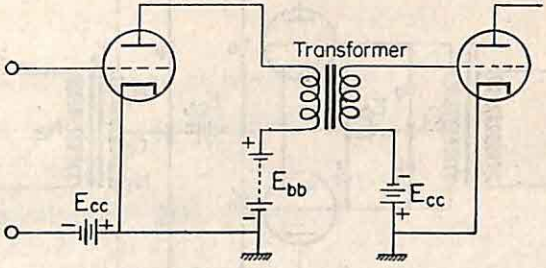


Fig. 8.9

The primary winding of the amplifier is connected to the plate circuit of the first tube while its secondary is connected to the grid of the second tube. Since in a transformer, there is no direct connection between its two windings, the d.c. plate voltage of the first tube is isolated from the second stage grid circuit.

The transformer coupling permits operation at high plate voltages and thus causing large amplification. In practice the output voltage of the first stage may be stepped up by the ratio of about 3 : 1 of the secondary-to-primary turns. These amplifiers are generally used for impedance matching and phase inversion to drive a push-pull power amplifier. These are also employed sometimes in tuned radio frequency and I.F. amplifiers.

8.7 Push-pull Amplifier

In an amplifier the output power may be increased by parallel operation of two tubes, i.e., by connecting plate-to-plate, grid-to-grid and cathode-to-cathode of the two tubes. Such a combination provides an output power twice that obtained in a single tube but the total distortion becomes greater.

A much improved method is to connect the two tubes such that their grids are excited by equal signals with 180° out of phase. Such a circuit configuration of two identical tubes, as shown in Fig. 8.10, is known as push-pull connection. In the figure T_1 and T_2 are respectively input and output push-pull transformers. It is assumed that the (i) transformers are ideal, the points G_1 and C_2 of which are true electrical centres of the windings, (ii) both the tubes have identical characteristics and (iii) the load R_L is a pure resistance.

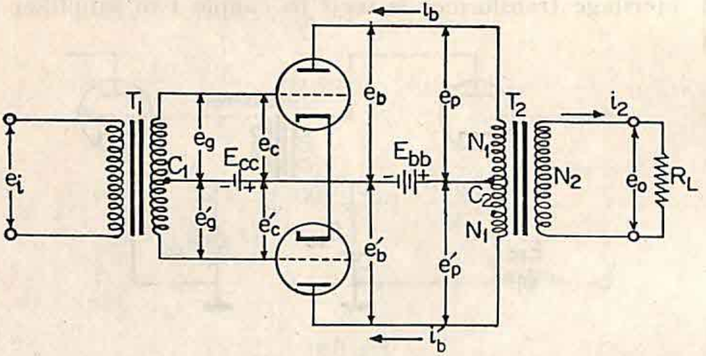


Fig. 8.10

On the primary of the input transformer T_1, the input signal source of voltage e_i is applied. Its secondary has three terminals, two of which are connected to the grids of the two tubes and the centre terminal is connected to the cathode through the bias battery E_{cc}. The voltage e_g and e_g' are such that while one is increasing the other is decreasing by the same amount, i.e., they are equal in amplitudes but in phase opposition.

Similarly, the two terminals of the output transformer T_2 are connected to the plates of the two tubes and the centre terminal is connected to the common cathode through the plate supply voltage source E_{bb}. The secondary of this transformer T_2 is connected to the load resistance R_L. Now, as the plate current i_b of one tube increases, the current i_b' of the second tube decreases by an equal amount. Or in other words, a.c. plate currents i_p and i_p' become equal in magnitude with 180° out of phase. The output voltages produced by these currents i_p and i_p' are added by using output push-pull transformer and hence the a.c. power becomes twice as that obtained in a single tube.

8.7.1 Operation

Let us consider the operation of the amplifier with no signal, small signal and large signal applied at the input.

CASE 1: When no signal is applied ((i.e., $e_i=0$)

We have, $e_g=e_g'=0$

$\therefore$ total instantaneous grid voltage

$$e_c = E_{cc} + e_g = E_{cc} + 0 = E_{cc}$$

$$= e_c' \quad \ldots \quad (8.23)$$

Again, $e_p = e_p' = 0$

$\therefore$ total instantaneous plate voltage

$$e_b = E_{bb} + e_p = E_{bb} + 0 = E_{bb}$$

$$= e_b' \quad \ldots \quad (8.24)$$

And total instantaneous plate current

$$i_b = i_b' = I_b \quad \ldots \quad (8.25)$$

We thus find that with no signal applied at the input, the two tubes have the same plate current I_b so that the total plate current becomes $2I_b$.

Further under no signal condition, the magnetomotive force in the upper half winding of N_1 turns sends magnetic flux in one direction and that in the lower half winding of N_1 turns sends magnetic flux in the opposite direction. This cancellation of d.c. magnetization in a push-pull configuration has an important advantage to avoid any harmonic distortion in the secondary side.

CASE 2: When small signal is applied at the input, the operation is confined to the linear region of tube characteristics. Then we have,

$$e_g = -e_g'$$

$$\therefore \quad e_c = E_{cc} + e_g \quad \ldots \quad (8.26)$$

$$\text{and} \quad e_c' = E_{cc} + e_g'$$

$$= E_{cc} - e_g \quad \ldots \quad (8.27)$$

Again $i_p = -i_p'$

$$\therefore \quad i_b = I_b + i_p \quad \ldots \quad (8.28)$$

$$\text{and} \quad i_b' = I_b + i_p' = I_b - i_p \quad \ldots \quad (8.29)$$

So, total current $= i_b + i_b'$

$$= 2I_b \quad \ldots \quad (8.30)$$

That is the current through the plate power source has no a.c. component and it has a value of $2I_b$.

Now, if the output transformer is considered ideal, the sum of the magnetomotive forces caused by current must be zero.

i.e., $i_bN_1-i_b'N_1-i_2N_2=0$

or, $N_1\,(i_b-i_b')=i_2N_2$

or,
$$i_2=\frac{N_1}{N_2}(i_b-i_b')$$
$$=\frac{N_1}{N_2}\cdot 2I_{pm}\cos\omega t \quad \text{(substituting the values of } i_b \text{ and } i_b'\text{)}$$
$$=2\frac{N_1}{N_2}\cdot i_p \qquad \ldots \qquad (8.31)$$

Therefore, in the output the two a.c. plate currents are additive in nature.

CASE 3: When large signal is applied, the operating point is not entirely travelled over the linear region of the tube characteristics. Rather, harmonics are generated in the plate current. If the sinosoidal grid signal voltage is of the form $e_g=E_{gm}\cos\omega t$, we can write,

$$i_b=I_b+I_{p_o}+I_{p_1m}\cos\omega t+I_{p_2m}\cos 2\omega t+I_{p_3m}\cos 3\omega t+\ldots \quad (8.32)$$

Similarly we can write an expression for i_b', simply replacing ωt by $(\omega t+\pi)$. Thus,

$$i_b'=I_b+I_{p_o}+I_{p_1m}\cos(\omega t+\pi)+I_{p_2m}\cos 2(\omega t+\pi)$$
$$+I_{p_3m}\cos 3(\omega t+\pi)+\ldots\ldots\ldots$$
$$=I_b+I_{p_o}-I_{p_1m}\cos\omega t+I_{p_2m}\cos 2\,\omega t$$
$$-I_{p_3m}\cos 3\omega t+\ldots\ldots\ldots\ldots \qquad \ldots \qquad (8.33)$$

So, total current $=i_b+i_b'$
$$=2I_b+2\,(I_{p_o}+I_{p_2m}\cos 2\omega t$$
$$+I_{p_4m}\cos 4\,\omega t+\ldots\ldots) \qquad \ldots \qquad (8.34)$$

That is the total current contains even harmonic terms in addition to the d.c. current $2I_b$ and an additional d.c. component $2I_{p_o}$.

Again, since,
$$i_2=\frac{N_1}{N_2}\,(i_b-i_b')$$

We get,
$$i_2=2\frac{N_1}{N_2}\,(I_{p_1m}\cos\omega t+I_{p_3m}\cos 3\omega t+\ldots\ldots\ldots) \qquad (8.35)$$

Thus in the output of push-pull amplifier the odd harmonics, first, third, etc., are only present under such condition.

8.7.2 Output Power

The a.c. equivalent circuit of the push-pull amplifier is drawn in Fig. 8.11. The total primary load into which the tubes work is that reflected from the secondary, as

$$R_{PP} = \left(\frac{2N_1}{N_2}\right)^2 . R_L \qquad \dots \qquad (8.36)$$

where R_{PP} is the plate-to-plate resistance.

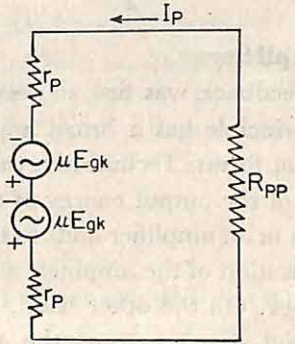


Fig. 8.11

Since the input signal is of the form

$$e_g = E_{gm} \cos \omega t = \sqrt{2}\, E_{gk} \cos \omega t \qquad \dots \qquad (8.37)$$

We have the plate current,

$$I_p = \frac{2\mu E_{gk}}{R_{PP}+2r_P}$$

$$= \frac{\mu E_{gk}}{\frac{R_{PP}}{2}+r_P} \qquad \dots \qquad (8.38)$$

∴ AC power delivered to the load

$$P_{ac} = I_p^2 . R_{PP}$$

$$= \left[\frac{\mu E_{gk}}{\frac{R_{PP}}{2}+r_P}\right]^2 . R_{pp}$$

$$= \left[\frac{\mu E_{gk}}{\frac{R_{PP}}{4}+\frac{r_P}{2}}\right]^2 . \frac{R_{PP}}{4} \qquad \dots \qquad (8.39)$$

Alternately, we can write,

$$P_{ac}=2\left[\frac{\mu E_{gk}}{\frac{R_{PP}}{2}+r_P}\right]^2\cdot\frac{R_{PP}}{2} \qquad \ldots \qquad (8.40)$$

This equation shows that the total output power obtained in a push-pull amplifier is twice that of a single tube when it is operating in the equivalent load resistance $\frac{R_{PP}}{2}$.

8.8 Feedback in Amplifiers

The principle of feedback was first successfully applied by H. S. Black in 1934. The principle has a broad application to any amplifying system of different forms. Technically, the term feedback means transferring a portion of the output energy of any device to its input. If the feedback voltage in an amplifier adds to the input signal voltage, it increases the amplification of the amplifier and it is called a positive or regenerative feedback. On the other hand, if the feedback voltage subtracts from the input signal voltage, the amplification decreases and the feedback is called a negative, inverse or degenerative feedback.

To understand the feedback system an amplifier with feedback arrangement is shown in Fig. 8.12. In this arrangement a part, $\mathbf{E}_f$ say, of the output voltage $\mathbf{E}_o$ is returned to the input which is added to the input signal voltage $\mathbf{E}_i$ for producing the grid to cathode voltage $\mathbf{E}_{gk}$. Mathematically we can write,

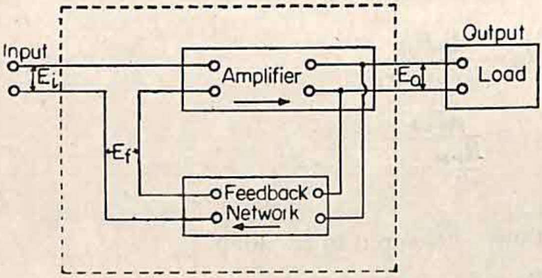


Fig. 8.12

$$\mathbf{E}_{gk}=\mathbf{E}_i+\mathbf{E}_f \qquad \ldots \qquad (8.41)$$

The complex voltage gain of the internal amplifier is given by,

$$\mathbf{A}=\frac{\mathbf{E}_o}{\mathbf{E}_{gk}} \qquad \ldots \qquad (8.42)$$

and the transfer voltage ratio,

$$\beta = \frac{\mathbf{E}_f}{\mathbf{E}_o} \quad \ldots \quad (8.43)$$

By using equations (8.42) and (8.43) we get,

$$\beta = \frac{\mathbf{E}_f}{\mathbf{A}\mathbf{E}_{g\,k}}$$

or, $$\mathbf{E}_f = \mathbf{A}\beta\, \mathbf{E}_{g\,k} \quad \ldots \quad (8.44)$$

The term $\mathbf{A}\beta$ is called the feedback factor or the return ratio. Now, substituting the value of $\mathbf{E}_f$ in equation (8.41) we get,

$$\mathbf{E}_{g\,k} = \mathbf{E}_i + \mathbf{A}\beta\mathbf{E}_{g\,k}$$

or, $$\mathbf{E}_{g\,k}\,(1 - \mathbf{A}\beta) = \mathbf{E}_i$$

$$\therefore \quad \mathbf{E}_{g\,k} = \frac{\mathbf{E}_i}{1 - \mathbf{A}\beta} \quad \ldots \quad (8.45)$$

Therefore, the gain with feedback, $\mathbf{A}'$ is given by,

$$\mathbf{A}' = \frac{\mathbf{E}_o}{\mathbf{E}_i} = \frac{\mathbf{A}\,\mathbf{E}_{g\,k}}{\mathbf{E}_i} = \frac{\mathbf{A}}{1 - \mathbf{A}\beta} \quad \ldots \quad (8.46)$$

The overall effective gain due to feedback is thus a function of the internal gain A and the proportion of the output feedback β.

If $|1 - \mathbf{A}\beta| < 1$, then gain $\mathbf{A}'$ is greater than $\mathbf{A}$. The feedback is then positive and the circuit is regenerative. Generally, a regenerative circuit gives decreased stability, increased gain and higher distortion.

If $|1 - \mathbf{A}\beta| > 1$, then gain $\mathbf{A}'$ is less than $\mathbf{A}$. The feedback is then negative and the circuit is degenerative. A degenerative circuit, in general, increases stability, lowers gain and reduces distortion and noise in an amplifier.

8.8.1 Feedback characteristics

(i) If $\mathbf{A}\beta = 1$, $1 - \mathbf{A}\beta = 0$

$\mathbf{A}'$ becomes infinite.

Infinite gain may be explained as a condition of the amplifier when output is obtained from zero input. The amplifier then becomes an oscillator having an output voltage independent of any external input voltage.

(ii) If $|\mathbf{A}\beta| \gg 1$, $1-\mathbf{A}\beta = -\mathbf{A}\beta$

$$\mathbf{A}' = \frac{\mathbf{A}}{-\mathbf{A}\beta} = -\frac{1}{\beta} \qquad \ldots \quad (8.47)$$

From these we may draw the following important conclusions:

(a) The feedback gain is inversely proportional to β. This means that the frequency response characteristic of the amplifier is inverse of the response characteristic of the network.

(b) The amplification is not dependent on $\mathbf{A}$, the complex voltage gain of the internal amplifier.

(c) The amplification is not dependent on the load impedance provided it does not form a part of the feedback.

(iii) Two types of feedback amplifiers are there. These are: (a) *voltage feedback* and (b) *current feedback*.

The feedback ratio β in a voltage feedback is independent of load impedance while in a current feedback β is dependent on the load impedance.

8.8.2 Feedback Effect on Frequency Distortion

Let us consider the case when the amplifier has an excessive gain at a certain frequency. Let at a particular frequency, $\mathbf{A}_1$ and $\mathbf{A}_1'$ are the voltage amplifications without and with feedback networks while $\mathbf{A}_2$ and $\mathbf{A}_2'$ be those at any other frequency. Then we can write,

$$\mathbf{A}_1' = \frac{\mathbf{A}_1}{1-\beta\mathbf{A}_1} \qquad \ldots \quad (8.48)$$

and $$\mathbf{A}_2' = \frac{\mathbf{A}_2}{1-\beta\mathbf{A}_2} \qquad \ldots \quad (8.49)$$

where the value of the feedback function β is considered identical at both the frequencies.

Using equations (8.48) and (8.49) we get,

$$\frac{\mathbf{A}_1'}{\mathbf{A}_2'} = \frac{\mathbf{A}_1}{1-\beta\mathbf{A}_1} \Big/ \frac{\mathbf{A}_2}{1-\beta\mathbf{A}_2} \qquad \ldots \quad (8.50)$$

If β is sufficiently large,

$$\frac{\mathbf{A}_1'}{\mathbf{A}_2'} = 1 \qquad \ldots \quad (8.51)$$

which shows that the voltage amplifications are not frequency dependent.

8.8.3 Cathode Follower

In a cathode follower amplifier the property of feedback is utilized. The circuit diagram of the unit is shown in Fig. 8.13. In the figure, the grid leak resistor R_g is connected between the grid and ground where the voltage source E_s is applied. The cathode is returned to the ground through a resistor R_k and the output voltage E_o is obtained across it. The plate terminal P is connected to the positive plate supply voltage E_{bb}.

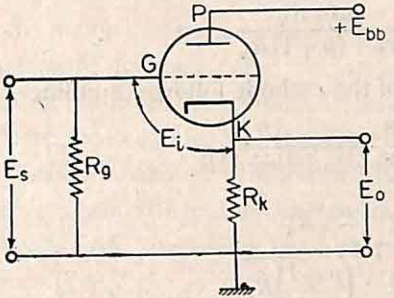


Fig. 8.13

The equivalent circuit of the cathode follower amplifier is shown in Fig. 8.14. The current I through the cathode resistor R_k from cathode to ground is,

$$\mathbf{I} = \frac{\mu \mathbf{E}_i}{r_p + R_k} \quad \ldots \quad (8.52)$$

where $\mathbf{E}_i = \mathbf{E}_s - \mathbf{E}_o$ is the voltage between the grid and the cathode.

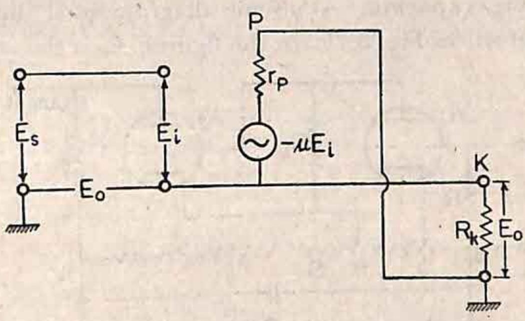


Fig. 8.14

Equation (8.52) can alternately be written as,

$$\mathbf{I} = \frac{\mu(\mathbf{E}_s - \mathbf{E}_o)}{r_p + R_k} \quad \ldots \quad (8.53)$$

∴ output voltage $\mathbf{E}_o$ across R_k is,

$$\mathbf{E}_o=\frac{\mu(\mathbf{E}_s-\mathbf{E}_o)}{r_p+R_k}\,.\,R_k$$

$$=\frac{\mu\mathbf{E}_s\,R_k}{r_p+(\mu+1)R_k} \qquad \ldots \qquad (8.54)$$

∴ the gain of the cathode follower amplifier,

$$\mathbf{A}=\frac{\mathbf{E}_o}{\mathbf{E}_s}=\frac{\mu R_k}{r_p+(\mu+1)R_k} \qquad \ldots \qquad (8.55)$$

$$=\frac{\dfrac{\mu}{r_p}\,.\,R_k}{1+\left(\dfrac{\mu+1}{r_p}\right)R_k}$$

Since $\mu+1\approx\mu$

$$\therefore \qquad \mathbf{A}=\frac{g_m\,R_k}{1+g_m\,R_k}\left(\because \quad g_m=\frac{\mu}{r_p}\right)$$

If $g_mR_k\gg1$ then **A** approaches towards unity. As the gain is nearly unity with high input and low output impedance, the output power becomes greater than the input. A cathode follower may therefore be considered as a power amplifier.

8.8.4 Direct Coupled Amplifier

In order to amplify a slowly varying voltage or a steady voltage, capacitance couplings are unsuitable. In such cases a direct connection is made between the plate of a first tube to the grid of the next without any intervening capacitor. A circuit diagram of a direct coupled amplifier is shown in Fig. 8.15. In the figures, R_g is the grid resistor at

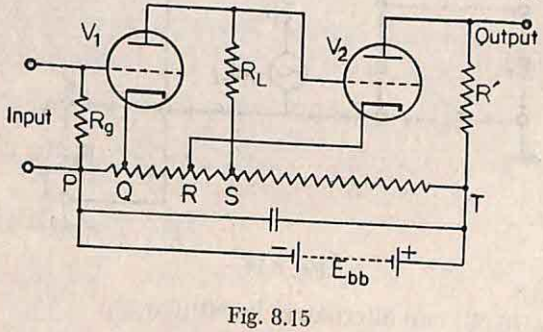


Fig. 8.15

the input and R_L is the load resistor connected at the plate of the first tube. The voltage distribution of the amplifier is made through the voltage divider P, Q, R, S, T which is connected across the d.c. supply E_{bb}. The most positive point T of the supply E_{bb} is connected through the resistor R' to the plate of the second tube.

In practice the valve characteristics change slightly with time due to the temperature increase, etc. To overcome the difficulty, degenerative feedback is applied, in general. In fact, the voltage divider arrangement is a complicated task. But when it is properly designed it becomes a distortionless amplifier with uniform frequency response from d.c. to above the audio range. Besides amplification of slow variations of input voltages D.C. amplifiers are also very useful for amplifying pulse signals.

Examples

1. A 12AU7 triode used as an amplifier has an amplification factor of 20 and a.c. plate resistance of 12 KΩ. Calculate the voltage gain of the amplifier for a load resistance of 18 KΩ.

Here, $\mu=20$, $r_P=12$ KΩ and $R_L=18$ KΩ

Now, voltage gain

$$A_0=\frac{\mu R_L}{r_P+R_L}$$

$$=\frac{20\times18}{12+18}=12.$$

2. A triode used as amplifier has an amplification factor of 20 and a.c. plate resistance of 10 KΩ. If the signal voltage applied to the grid has a 3-volt peak swing, calculate the value of the load current and the output voltage. The load resistance is 15 KΩ.

Here $\mu=20$

$r_P=10\ \text{K}\Omega=10\times10^3\,\Omega$

$R_L=15\ \text{K}\Omega=15\times10^3\,\Omega$

$E_S=3$ volts.

Now, the load current $I_P=\dfrac{\mu\dfrac{E_S}{\sqrt{2}}}{r_P+R_L}$

$$=\frac{20\times3\times0.707}{(10+15)\times10^3}=1.69\times10^{-3}\text{ amps.}$$

and the output voltage, $E_0=I_P\times R_L$

$$=16.9\times15\times10^{-3}\times10^3$$

$$=25.35\text{ volts.}$$

3. A triode valve used as an amplifier has $\mu=15$ and $r_P=12$ KΩ. If the anode load consists of a resistance and inductance of values 20 KΩ and 7500 μH respectively, calculate the voltage gain of the amplifier. Given that the input voltage has a frequency of 600 kHz.

Here, $\mu=15$

$$r_P=12\ \text{K}\Omega=12\times10^3\ \Omega$$

$$R_L=20\ \text{K}\Omega=20\times10^3\ \Omega$$

$$L=7500\ \mu\text{H}=75\times10^{-4}\ \text{H}$$

$$f=600\ \text{kHz}=600\times10^3\ \text{Hz}$$

Now, voltage gain $A=\dfrac{\mu Z_L}{r_P+Z_L}$

where

$$Z_L=\sqrt{R_L^2+X_L^2}$$

$$=\sqrt{R_L^2+(2\pi fL)^2}$$

$$=\sqrt{(20\times10^3)^2+(2\times3.14\times600\times10^3\times75\times10^{-4})^2}$$

$$=34653\ \Omega$$

$$\therefore \quad A=\frac{15\times34653}{12000+34653}$$

$$=11.14.$$

4. An amplifier has a gain of 6000 $\angle$O. When negative feedback is applied, the gain is reduced to 1000 $\angle$O. Find the feedback ratio β.

The feedback gain A' is given by,

$$A'=\frac{A}{1-A\beta}$$

Here, $A'=1000$

and $A=6000$

$$\therefore \quad 1000=\frac{6000}{1-6000\,\beta}$$

or, $1-6000\,\beta=6$

$$\therefore \quad \beta=-\frac{5}{6000}=-0.00083.$$

Self-Test

Read each of the following and provide the appropriate words:

(a) The tuned amplifiers are used to amplify an electrical signal containing a — frequency.

(b) A class *AB* amplifier is designed such that the plate current flows for less than half cycle of the input voltage. (True/False)

(c) The amplification of a pentode becomes extremely —. (high/low)

(d) The three main types of distortions are the amplitude, frequency and — distortion.

(e) Amplitude distortion is caused by non-linear operation. (True/False)

(f) The term — means transferring a portion of the output energy of any device to its input.

(g) The feedback ratio β in a voltage feedback is — of load impedance. (dependent/independent)

(h) A cathode follower may be considered as a — amplifier.

Review Questions

1. What are amplifiers? How are they classified?

2. Describe with circuit diagram the operation of a single stage voltage amplifier. Find its voltage gain.

3. Obtain expressions for voltage gain of an untuned class A_1 amplifier when (i) Z_L is purely resistive, (ii) Z_L is purely inductive and (iii) Z_L is complex inductive.

4. Discuss the advantages of a pentode amplifier over a triode.

5. What is meant by distortion in amplifiers? Define the three main types of distortions.

6. Explain with necessary diagram the operation of a RC coupled amplifier. Calculate expressions for voltage gain when the frequency is (i) low, (ii) medium and (iii) high.

7. What is meant by a transformer coupled amplifier? Give its circuit diagram.

8. Define a push-pull amplifier. Explain it with a necessary diagram. Consider the operation of a push-pull amplifier when (i) no signal, (ii) small signal and (iii) large signal is applied at the input.

9. Obtain an expression for the total output power of a push-pull amplifier.

10. Define 'positive' and 'negative' feedback in amplifiers. Draw the block diagram of a negative feedback amplifier.

11. Derive an expression for the voltage gain of an amplifier of gain A when subjected to negative feedback with a feedback factor β.

12. Discuss the effects of negative voltage feedback on amplifier characteristics. Show the feedback effect on frequency distortion.

13. What is a cathode follower amplifier? Find expression for its voltage gain. Give its equivalent circuit.

14. Briefly describe the direct coupled amplifier.

15. If the voltage gain of a triode amplifier is 9.375 for an a.c. resistance of 12×10^3 ohms, find the amplification factor when anode load consists of non-inductive resistance of value 20×10^3 ohms. (*Ans.* 15)

16. A triode used as an amplifier has $\mu=50$, $R_L=10$ K and $r_p=20$ K. Determine the output voltage for an input voltage of 5 volts. (*Ans.* 43.3 volts)

17. A negative feedback amplifier has a gain of 66.02 dB and the attenuation of the feedback path is 80 dB. Find the voltage gain of the amplifier when no feedback arrangement is made. (*Ans.* 2500)

CHAPTER 9

OSCILLATORS

9.1 Introduction

An oscillator is an electronic device used for converting d.c. power into a.c. power. Because of this property of conversion from d.c. to a.c. it may also be called as an inverter. An oscillator generates alternating voltages or currents over a wide frequency range and the frequency of oscillation may be varied easily. Oscillators are used for various purposes such as in radio and TV transmitters and receivers, in radar, for high frequency heating, etc.

An oscillator has essentially three different parts. These are: (a) Internal amplifier, (b) Feedback network and (c) Amplitude limiting device.

Internal amplifier—The oscillator is nothing but an amplifier with infinite voltage gain. The infinite gain is made properly by feedback arrangement or by using a negative resistor.

Feedback network—We know that the voltage gain of a feedback amplifier may be expressed as,

$$\mathbf{A}_f=\frac{\mathbf{A}}{1-\mathbf{A}\beta} \qquad \cdots \qquad (9.1)$$

where **A** is the complex voltage gain and β is the feedback ratio.

Now, if $1-\mathbf{A}\beta=0$, $\mathbf{A}_f$ becomes infinite. The amplifier then behaves as an oscillator.

Amplitude limiting device—In an oscillator the amplitude of oscillation builds up until the negative resistance of the tube becomes equal to the positive resistance of the associated load circuit and thus forming an automatic limiting device.

9.2 Classification

Oscillators may be broadly classified in three different categories, viz., (a) depending on the method of producing oscillations, (b) depending on the waveform of the generated voltage and (c) depending on the frequency of the generated voltage.

According to the method (a), oscillators are subdivided as: (i) *feedback oscillator* and (ii) *negative resistance oscillator*. In a feedback oscillator a portion of the output voltage is fedback to the input so that the condition $A\beta=1$ is satisfied. In a negative resistance oscillator, on the other hand, a negative resistance is produced in the amplifier tube for neutralizing the positive resistance of the oscillating circuit.

According to the method (b), oscillators are subdivided as: (i) *relaxation oscillator* and (ii) *sine wave oscillator*. A relaxation oscillator generates currents or voltages which abruptly change one or more times in an oscillation cycle. A sine wave oscillator, on the other hand, generates sinusoidal voltages.

According to the method (c), oscillators are subdivided as: (i) *audio frequency oscillator*, (ii) *radio frequency oscillator*, (iii) *ultra high frequency* (UHF) and *microwave oscillator*. An audio frequency oscillator generates voltages of frequency to about 15 to 20 kHz, a radio frequency oscillator in the range of about 20 kHz to 30 MHz while UHF and microwave oscillators have frequency above 30 MHz.

9.3 Sine Wave Oscillators

Sine wave oscillators are either negative resistance type or feedback type. Feedback types are divided into (a) *L-C resonant circuit oscillators* and (b) *R-C oscillators.*

L-C oscillators used mostly in common practice are: (i) *tuned plate oscillator*, (ii) *tuned grid oscillator*, (iii) *Hartley oscillator* and (iv) *Colpitts oscillator*. On the other hand, R-C oscillators of two important types are: (i) *Phase shift oscillator* and (ii) *Wien Bridge oscillator*. There are also a few other important sine wave oscillators suited for specific uses such as crystal oscillator, etc.

In the following sections we discuss all the above types briefly.

9.4 Tuned Plate Oscillator

Tuned plate circuit is a simple form of oscillator shown in Fig. 9.1(a). In this oscillator, the anode load consists of a parallel tuned

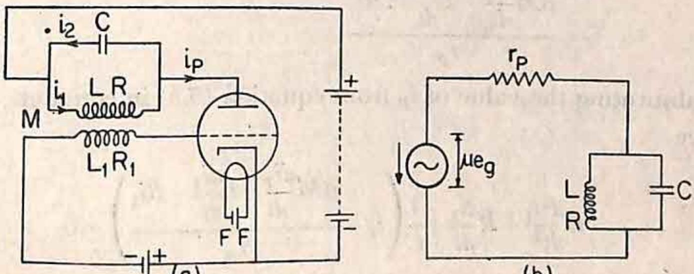


Fig. 9.1

circuit which is inductively coupled to the coil of the tuned circuit for the grid excitation. If the induced voltage in the grid circuit becomes greater than a certain critical value, continuous oscillation is produced. The equivalent circuit of the tuned plate oscillator is shown in Fig. 9.1(b).

By applying Kirchhoff's second law to the resonant circuit we can write,

$$L\frac{di_1}{dt}+Ri_1+\frac{1}{C}\int i_2\,dt=0$$

or, $$L\frac{d^2i_1}{dt^2}+R\frac{di_1}{dt}+\frac{1}{C}i_2=0$$

or, $$L\frac{d^2i_1}{dt^2}+R\frac{di_1}{dt}+\frac{1}{C}(i_1-i_p)=0 \qquad (\because\ i_2=i_1-i_p) \qquad \ldots \quad (9.2)$$

Here, $$i_p=g_m e_g+\frac{e_p}{r_p}$$

$$=\frac{\mu e_g+e_p}{r_p} \qquad \ldots \quad (9.3)$$

If HT is kept constant, the sum of the instantaneous changes in voltage across it must be zero.

$$\therefore \quad L\frac{di_1}{dt}+Ri_1+e_p=0$$

or, $$e_p=-L\frac{di_1}{dt}-Ri_1 \qquad \ldots \quad (9.4)$$

Again, $$e_g=M\frac{di_1}{dt}$$

$\therefore$ from equations (9.3) and (9.4) we get,

$$i_p=\frac{\mu M\frac{di_1}{dt}-L\frac{di_1}{dt}-Ri_1}{r_p} \qquad \ldots \quad (9.5)$$

Substituting the value of i_p from equation (9.5) in equation (9.2) we have,

$$L\frac{d^2i_1}{dt^2}+R\frac{di_1}{dt}+\frac{1}{C}\left(i_1-\frac{\mu M\frac{di_1}{dt}-L\frac{di_1}{dt}-Ri_1}{r_p}\right)=0$$

or, $$L\frac{d^2i_1}{dt^2}+\left(R+\frac{L}{Cr_p}-\frac{\mu M}{Cr_p}\right)\frac{di_1}{dt}+\frac{1}{C}\left(1+\frac{R}{r_p}\right)i_1=0 \ \ldots \quad (9.6)$$

If the circuit oscillates with a fixed amplitude, the coefficient of the damping term $\frac{di_1}{dt}$ will be zero, i.e.,

$$R+\frac{L}{Cr_p}-\frac{\mu M}{Cr_p}=0$$

$$\therefore \qquad M=\frac{1}{\mu}(L+Cr_pR) \qquad \ldots \qquad (9.7)$$

This equation giving the limiting value for M, is known as the maintenance equation. It may be expressed in terms of g_m, the mutual conductance of the valve.

It is seen that the circuit will be oscillatory if,

$$g_m \geqslant \frac{L}{Mr_p}+\frac{RC}{M} \qquad \ldots \qquad (9.8)$$

The frequency of oscillation is given by,

$$\frac{\omega}{2\pi}=\frac{1}{2\pi}\sqrt{\frac{1}{LC}\left(1+\frac{R}{r_p}\right)}$$

$$\simeq\frac{1}{2\pi\sqrt{LC}}\left(1+\frac{R}{2r_p}\right)$$

$$\text{or,} \qquad f\simeq f_R\left(1+\frac{R}{2r_p}\right) \qquad \ldots \qquad (9.9)$$

As $R \ll r_p$, equation (9.9) suggests that the frequency generated f is only slightly greater than the resonant frequency f_R.

9.5 Tuned Grid Oscillator

The circuit diagram of a tuned grid oscillator is shown in Fig. 9.2(a). In this oscillator, the tuned circuit is placed between the grid

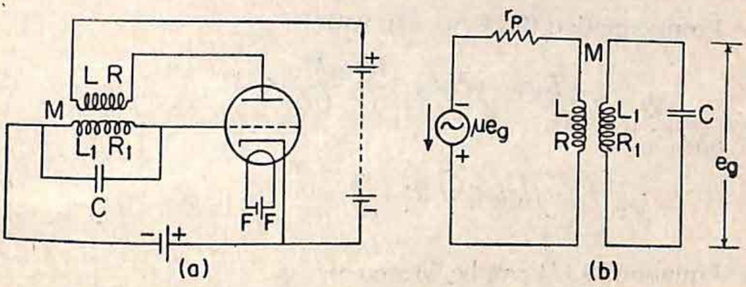


Fig. 9.2

and cathode and coupled to the anode of the valve by mutual inductance. The equivalent circuit of the oscillator is shown in Fig. 9.2(b).

In this case, we have,

$$\mu e_g = I_p\,(R+j\omega L+r_p) - j\omega MI \quad \ldots \quad (9.10)$$

and

$$j\omega MI_p = I\left(R_1+j\omega L_1+\frac{1}{j\omega C}\right) \quad \ldots \quad (9.11)$$

$\because\ e_g = \frac{I}{j\omega C}$, we can rewrite equation (9.10) as,

$$\mu\frac{I}{j\omega C} = I_p\,(R+j\omega L+r_p) - j\omega MI$$

or,

$$\left(\frac{\mu}{j\omega C}+j\omega M\right)I = I_p\,(R+j\omega L+r_p)$$

or,

$$\frac{I}{I_p} = \frac{R+j\omega L+r_p}{\frac{\mu}{j\omega c}+j\omega M} \quad \ldots \quad (9.12)$$

Again from equation (9.11) we have,

$$\frac{I}{I_p} = \frac{j\omega M}{R_1+j\omega L_1+\frac{1}{j\omega C}} \quad \ldots \quad (9.13)$$

By equations (9.12) and (9.13),

$$\frac{R+j\omega L+r_p}{\frac{\mu}{j\omega C}+j\omega M} = \frac{j\omega M}{R_1+j\omega L_1+\frac{1}{j\omega C}}$$

or,

$$(j\omega L+r_p)\left(R_1+j\omega L_1+\frac{1}{j\omega C}\right) = j\omega M\left(\frac{\mu}{j\omega C}+j\omega M\right) \quad (9.14)$$

($\because$ $R \ll r_p$, it is neglected)

From equation (9.14) we can write,

$$R_1 r_p - \omega^2 LL_1 + \frac{L}{C} = \frac{\mu M}{C} - \omega^2 M^2 \quad \ldots \quad (9.15)$$

and

$$\omega L_1 r_p + \omega LR_1 - \frac{r_p}{\omega C} = 0 \quad \ldots \quad (9.16)$$

Equation (9.15) can be written as,

$$CR_1 r_p - \omega^2 L\,L_1 C + L = \mu M - \omega^2 M^2 C \quad \ldots \quad (9.17)$$

If the grid circuit is resonant,

$$\omega^2 L_1 C \simeq 1$$

then, $$CR_1 r_p = \mu M - \frac{M^2}{L_1}$$

$$= \mu M\left(1 - \frac{M}{\mu L_1}\right)$$

$$\therefore \quad \frac{M}{\mu L_1} \ll 1, \text{ we have}$$

$$M = \frac{CR_1 r_p}{\mu} = \frac{CR_1}{g_m} \qquad \ldots \qquad (9.18)$$

$\therefore$ for the maintenance of oscillation,

$$g_m \geqslant \frac{CR_1}{M} \qquad \ldots \qquad (9.19)$$

Again the frequency generated can be obtained by using equation (9.16). We have,

$$\omega L_1 r_p + \omega L R_1 = \frac{r_p}{\omega C}$$

or, $$\omega^2 L_1 C r_p + \omega^2 L C R_1 = r_p$$

$$\therefore \quad \omega^2 = \frac{r_p}{L_1 C r_p + LCR_1}$$

or, $$\frac{\omega}{2\pi} = \frac{1}{2\pi\sqrt{L_1 C\left(1 + \frac{LR_1}{L_1 r_p}\right)}}$$

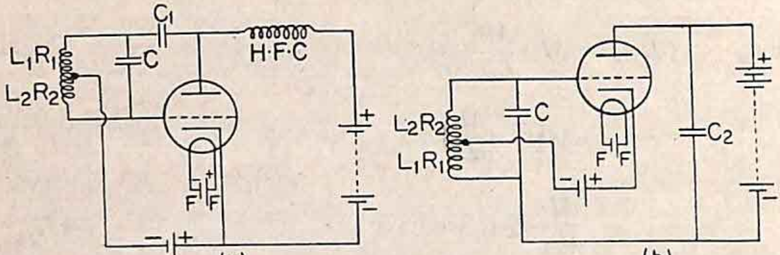
or, $$f = f_R\left(1 - \frac{LR_1}{2L_1 r_p}\right) \qquad \ldots \qquad (9.20)$$

where, $$f_R = \frac{1}{\frac{1}{2\pi}\sqrt{L_1 C}}$$

Therefore in this case the frequency generated is slightly less than the resonant frequency of the circuit.

9.6 Hartley Oscillator

Fig. 9.3 shows two forms of Hartley oscillator circuit. In this oscillator, a single tapped coil is utilized instead of two separate coils as used before. Fig. 9.3(a) shows a shunt fed circuit and Fig. 9.3(b) is for series fed circuit.



(a) (b)

Fig. 9.3

In the shunt fed arrangement the tuned circuit and the valve are in parallel with the HT source. To avoid short-circuiting, an impedance (high frequency choke) is inserted here between the anode and the positive terminal of the HT. Also, to block the direct potential from the grid a capacitor C_1 is included. In the series fed arrangement of the oscillator the tuned circuit, valve and the HT all are connected in series. As a result, the oscillatory current flows through the HT source and so it is shunted by a low reactance capacitor C_2. Neglecting the capacitors C_1, C_2 and also the high frequency choke used we can draw a simplified equivalent circuit of the two arrangements as shown in Fig. 9.4. In each circuit the total inductance L is given by,

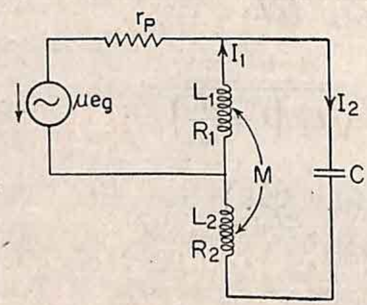


Fig. 9.4

$$L = L_1 + L_2 + 2M \qquad \cdots \quad (9.21)$$

Now, from the equivalent circuit we have,

$$\mu e_g = I_p r_p + I_1(R_1 + j\omega L_1) + I_2 j\omega M \qquad \cdots \quad (9.22)$$

$$e_g = I_2\,(R_2 + j\omega L_2) + I_1 j\omega M \qquad \cdots \quad (9.23)$$

and $$I_p = I_1 - I_2 \qquad \cdots \quad (9.24)$$

Substituting the values of I_p and e_g in equation (9.22) we get,

$$\mu[I_2(R_2+j\omega L_2)+I_1 j\omega M]=(I_1-I_2)r_p+I_1(R_1+j\omega L_1)+I_2 j\omega M$$

or, $$I_1[r_p+R_1+j\omega(L_1-\mu M)]=I_2(r_p+\mu R_2+j\omega\,(\mu L_2-M)]$$

$$\therefore \quad I_1=\frac{I_2[r_p+\mu R_2+j\omega(\mu L_2-M)]}{r_p+R_1+j\omega(L_1-\mu M)} \qquad \dots \qquad (9.25)$$

Round the tuned circuit the voltages are given by,

$$I_1(R_1+j\omega L_1)+I_2 j\omega M+I_2(R_2+j\omega L_2)+I_1 j\omega M+\frac{I_2}{j\omega C}=0$$

or, $$I_1[R_1+j\omega(L_1+M)]+I_2\left[R_2+j\omega(L_2+M)+\frac{1}{j\omega C}\right]=0 \qquad (9.26)$$

Substituting the value of I_1 from equation (9.25) in equation (9.26) we get,

$$I_2\Big[\{r_p+\mu R_2+j\omega(\mu L_2-M)\}\{R_1+j\omega(L_1+M)\}$$
$$+\{r_p+R_1+j\omega(L_1-\mu M)\}\left\{R_2+j\omega(L_2+M)+\frac{1}{j\omega C}\right\}\Big]=0$$
$$\dots \qquad (9.27)$$

The circuit will be oscillatory when the quantity within the square bracket vanishes. The quantity is separated below into real and imaginary parts. The real part gives the condition for maintenance of oscillation while the frequency generated is obtained from the imaginary part.

The real terms of equation (9.27) give,

$$r_p(R_1+R_2)+R_1R_2(1+\mu)+\frac{L_1-\mu M}{C}-\omega^2(L_2+M)\,(L_1-\mu M)$$
$$-\omega^2(\mu L_2-M)\,(L_1+M)=0$$

Neglecting the term $R_1R_2\,(1+\mu)$, as it is very small, we can write,

$$r_p(R_1+R_2)+\frac{L_1-\mu M}{C}=\omega^2(L_1L_2-M^2)(1+\mu)$$

or, $$\frac{L_1-\mu M}{C}=\omega^2(L_1L_2-M^2)\,(1+\mu)-r_p(R_1+R_2)$$

Now, $$\omega^2\simeq\frac{1}{(L_1+L_2+2M)C}$$

$$\therefore \qquad \frac{L_1-\mu M}{C}=\frac{(L_1L_2-M^2)\,(1+\mu)}{(L_1+L_2+2M)C}-r_p(R_1+R_2)$$

from which

$$\mu=\frac{L_1+M}{L_2+M}+\frac{r_p(R_1+R_2)\,(L_1+L_2+2M)C}{(L_1+M)\,(L_2+M)}$$

If the resistance of the coil is neglected, we get,

$$\mu=\frac{L_1+M}{L_2+M} \qquad \cdots \qquad (9.28)$$

Equation (2.28) gives the condition of oscillation in a Hartley oscillator. The equation shows that the circuit can be adjusted for oscillation by changing the tapping point of the coil.

Again, the imaginary terms of equation (9.27) give,

$$\omega^2[r_p(L_1+M+L_2+M)+L_1R_2(1+\mu)+L_2R_1(1+\mu)]=\frac{r_p+R_1}{C}.$$

If $L_1R_2\,(1+\mu)$ and $L_2R_1\,(1+\mu)$ are small in comparison to $r_p(L_1+M+L_2+M)$, we have,

$$\omega^2=\frac{r_p+R_1}{Cr_p(L_1+L_2+2M)}$$

or, $$\omega=\sqrt{\frac{r_p+R_1}{Cr_p(L_1+L_2+2M)}}$$

or $$f\simeq f_R\left(1+\frac{R_1}{2r_p}\right) \qquad \cdots \qquad (9.29)$$

where, $$f_R=\frac{1}{2\pi\sqrt{(L_1+L_2+2M)C}}$$

Equation (9.29) gives the frequency of oscillation of a Hartley oscillator in terms of the resonant frequency f_R. The frequency of oscillation may be varied conveniently by using a variable capacitor C in the circuit.

9.7 Colpitts Oscillator

The circuit diagram of a Colpitts oscillator is shown in Fig. 9.5. In this oscillator, the cathode is connected to the tapping point of the capacitor instead of the coil. A grid leak resistor R_g is used to provide a conducting path between the grid and the cathode. As the circuit is shunt fed a high frequency choke (HFC) is also essential here. In addition a low reactance capacitor C' is utilized to prevent direct anode voltage from the grid. If we neglect these extra components, the simplified equivalent circuit will be similar to that as shown in Fig. 9.4 for Hartley oscillator.

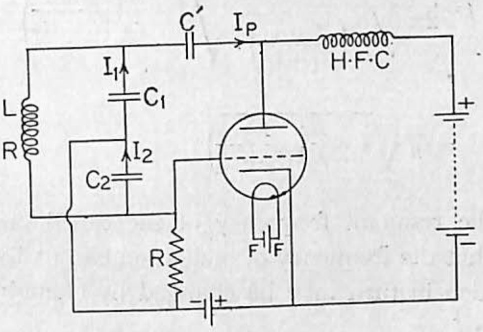


Fig. 9.5.

In this case we have,

$$\mu e_g = I_p r_p + \frac{I_1}{j\omega C_1} \qquad \ldots \qquad (9.30)$$

$$e_g = \frac{I_2}{j\omega C_2} \qquad \ldots \qquad (9.31)$$

$$I_p = I_1 - I_2 \qquad \ldots \qquad (9.32)$$

and
$$\frac{I_1}{j\omega C_1} + I_2\left(R + j\omega L + \frac{1}{j\omega C_2}\right) = 0 \qquad \ldots \qquad (9.33)$$

Solving these equations for voltages and currents we can calculate, as before, the oscillatory condition and the frequency of oscillation of the circuit.

The condition for the circuit to be oscillatory may be expressed as,

$$1 + \mu = \left[\frac{C_1 + C_2}{C_1} + \frac{r_p R(C_1 + C_2)}{L}\right]\left[1 + \frac{RC_2}{r_p(C_1 + C_2)}\right]$$

$\because$ $RC_2 \ll r_p\ (C_1 + C_2)$ we have,

$$1 + \mu = \frac{C_1 + C_2}{C_1} + \frac{r_p R(C_1 + C_2)}{L}$$

or,
$$\mu = \frac{C_2}{C_1} + \frac{r_p R(C_1 + C_2)}{L} \qquad \ldots \qquad (9.34)$$

Again, the frequency of oscillation f is given by,

$$f=\frac{1}{2\pi\sqrt{L\left(\frac{C_1C_2}{C_1+C_2}\right)}}\sqrt{1+\frac{R}{r_p}\left(\frac{C_2}{C_1+C_2}\right)}$$

$$=f_R\sqrt{1+\frac{R}{r_p}\left(\frac{C_2}{C_1+C_2}\right)} \tag{9.35}$$

where f_R is the resonant frequency of the tuned circuit. Equation (9.35) shows that the frequency of oscillation can easily be altered by varying f_R which in turn may be changed by changing the value of the inductance L.

Series fed is not possible in Colpitts oscillator, since with series fed no d.c. path is available from plate to cathode.

It is interesting to note here that the frequency of oscillation in Colpitts oscillator is greater than the resonant frequency while in Hartley oscillator it is less than the resonant frequency of the tuned circuit.

9.8 Phase Shift Oscillator

The circuit diagram of the RC phase shift oscillator is shown in Fig. 9.6. In this oscillator, the output across the load resistance R_L is fedback through a phase shift network. The feedback network has three R–C sections, each producing a phase shift of 60°. The distribution of currents in the three sections is shown in Fig. 9.7, assuming that $C_1=C_2=C_3=C$ and $R_1=R_2=R_3=R$.

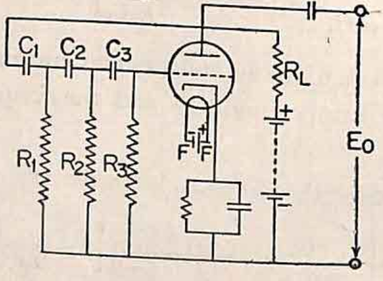


Fig. 9.6

An analysis of Fig. 9.7 gives the following relations,

$$\mathbf{E}_p=(\mathbf{I}_1+\mathbf{I}_2+\mathbf{I}_3)\,\frac{1}{j\omega C}+\mathbf{I}_3R \quad \dots \quad (9.36)$$

$$\mathbf{I}_1R=\mathbf{E}_g \quad \dots \quad (9.37)$$

$$\mathbf{I}_2R=\mathbf{I}_1\frac{1}{j\omega C}+\mathbf{I}_1R \quad \dots \quad (9.38)$$

$$\mathbf{I}_3R=(\mathbf{I}_1+\mathbf{I}_2)\,\frac{1}{j\omega C}+\mathbf{I}_2R \quad \dots \quad (9.39)$$

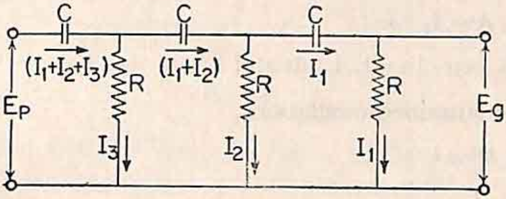


Fig. 9.7

Using equation (9.37) to equation (9.39) the expressions for currents I_1, I_2 and I_3 can alternately be written as below:

$$\mathbf{I}_1=\frac{\mathbf{E}_g}{R} \quad \dots \quad (9.40)$$

$$\mathbf{I}_2=\frac{\mathbf{I}_1}{R}\cdot\frac{1}{j\omega C}+\mathbf{I}_1$$

$$=\frac{\mathbf{E}_g}{j\omega CR^2}+\frac{\mathbf{E}_g}{R} \text{ (substituting the value of } \mathbf{I}_1\text{)}$$

$$=\mathbf{E}_g\left(\frac{1}{j\omega CR^2}+\frac{1}{R}\right) \quad \dots \quad (9.41)$$

and $$\mathbf{I}_3=(\mathbf{I}_1+\mathbf{I}_2)\,\frac{1}{j\omega CR}+\mathbf{I}_2$$

$$=\mathbf{E}_g\left[\left(\frac{1}{R}+\frac{1}{R}+\frac{1}{j\omega CR^2}\right)\frac{1}{j\omega CR}+\left(\frac{1}{j\omega CR^2}+\frac{1}{R}\right)\right]$$

$$=\frac{\mathbf{E}_g}{R^2}\left(R+\frac{3+\frac{1}{j\omega CR}}{j\omega C}\right) \quad \dots \quad (9.42)$$

Again, from equation (9.36) we have,

$$\mathbf{E}_p=(\mathbf{I}_1+\mathbf{I}_2+\mathbf{I}_3)\,\frac{1}{j\omega C}+(\mathbf{I}_1+\mathbf{I}_2)\,\frac{1}{j\omega C}+\frac{\mathbf{I}_1}{j\omega C}+\mathbf{E}_g \quad (9.43)$$

Substituting the values of $\mathbf{I}_1$, $\mathbf{I}_2$ and $\mathbf{I}_3$ from equation (9.40) to equation (9.42) and solving we get,

$$\beta=\frac{\mathbf{E}_g}{\mathbf{E}_p}$$

$$=\frac{1}{\left(1-\frac{5}{\omega^2C^2R^2}\right)+j\left(\frac{1}{\omega^3C^3R^3}-\frac{6}{\omega CR}\right)} \quad \ldots \quad (9.44)$$

The complex voltage gain $\mathbf{A}$ of the amplifier can be written as,

$$\mathbf{A}=A_r+jA_i$$

For the given circuit $A_i=0$ and hence $A=A_r$.

Again for sustained oscillations,

$$\mathbf{A}\beta=1$$

or, $$\frac{1}{\beta}=\mathbf{A}=A_r$$

∴ from equation (9.44) we can write,

$$\frac{1}{\beta}=A_r=\left(1-\frac{5}{\omega^2C^2R^2}\right)+j\left(\frac{1}{\omega^3C^3R^3}-\frac{6}{\omega CR}\right) \quad \ldots \quad (9.45)$$

The expression for frequency is obtained by equating the imaginary part of equation (9.45). Thus,

$$\frac{1}{\omega^3C^3R^3}-\frac{6}{\omega CR}=0$$

or, $$\omega=\frac{1}{\sqrt{6}\,CR}$$

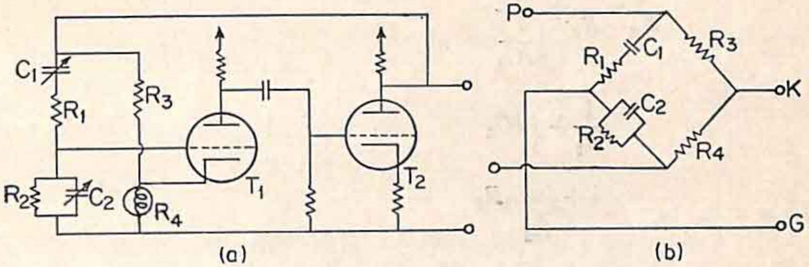
∴ $$f=\frac{1}{2\pi\sqrt{6}\,CR} \quad \ldots \quad (9.46)$$

Since the variation of R and C in equation (9.46) is too complicated, the oscillator is used usually where a constant frequency is required. The frequency stability of the phase shift oscillator is, however, not as good as can be achieved with other RC oscillators.

9.9 Wien Bridge Oscillator

The circuit diagram of the Wien Bridge oscillator is shown in Fig. 9.8(a). The oscillator, as shown, is a two-stage R–C coupled amplifier of which a part of the output voltage is fedback to the input.

The reason for the name is found in the form of the coupling network to tube T_1, the bridge nature of which is given in Fig. 9.8(b).



(a) (b)

Fig. 9.8

The tungsten filament lamp R_4 has a positive temperature coefficient of resistance and is used for automatic control of the amplitude of oscillations. When the oscillator works if the amplitude of its oscillation increases, the lamp becomes hotter causing an increase of R_4. Consequently, the grid cathode potential of the tube T_1 reduces, causing a decrease of the amplitude.

In the Wien Bridge oscillator, oscillations are produced when the feedback voltage becomes equal to the magnitude and phase of the input voltage of the first stage.

Let, $\mathbf{E}_f$ = feedback voltage,

$\mathbf{E}_i$ = input voltage,

$\mathbf{A}$ = complex voltage gain

$= A_r + jA_i$

and β = feedback factor.

Then we may write,

$$\mathbf{E}_f = \mathbf{A}\,\mathbf{E}_i\,\beta \qquad \cdots \qquad (9.47)$$

Here,

$$\beta = \frac{\mathbf{Z}_\beta}{\mathbf{Z}_L} \qquad \cdots \qquad (9.48)$$

where, $\mathbf{Z}_\beta$ = complex transfer impedance,

$\mathbf{Z}_L$ = impedance of the load.

So equation (9.47) can be rewritten as,

$$\mathbf{E}_f = \mathbf{A}\,\mathbf{E}_i\,\frac{\mathbf{Z}_\beta}{\mathbf{Z}_L} \qquad \cdots \qquad (9.49)$$

Now, from the circuit we have,

$$\frac{1}{\mathbf{Z}_\beta}=\frac{1}{R_2}+\frac{1}{\dfrac{1}{j\omega C_2}}$$

$$=\frac{1}{R_2}+j\omega C_2$$

$$=\frac{1+j\omega C_2R_2}{R_2}$$

$$\therefore \qquad \mathbf{Z}_\beta=\frac{R_2}{1+j\omega C_2R_2} \qquad \dots \qquad (9.50)$$

and $\mathbf{Z}_L=\mathbf{Z}_\beta+\mathbf{Z}'$

where, $\mathbf{Z}'=\left(R_1+\dfrac{1}{j\omega C_1}\right)$

$$\therefore \qquad \mathbf{Z}_L=\frac{R_2}{1+j\omega C_2R_2}+\left(R_1+\frac{1}{j\omega C_1}\right) \qquad \dots \qquad (9.51)$$

Thus by equations (9.49), (9.50) and (9.51) we have,

$$\mathbf{E}_f=\mathbf{A}\,\mathbf{E}_i\,\frac{\dfrac{R_2}{1+j\omega C_2R_2}}{\dfrac{R_2}{1+j\omega C_2R_2}+\left(R_1+\dfrac{1}{j\omega C_1}\right)} \qquad \dots \qquad (9.52)$$

For sustained oscillations, $\mathbf{E}_f=\mathbf{E}_i$

$$\therefore \qquad \mathbf{A}=1+\frac{\left(R_1+\dfrac{1}{j\omega C_1}\right)}{R_2/(1+j\omega C_2R_2)}$$

$$=1+\frac{(1+j\omega C_1R_1)\,(1+j\omega C_2R_2)}{j\omega C_1R_2}$$

$$=1+\frac{(1-\omega^2C_1C_2R_1R_2)+j\omega(C_1R_1+C_2R_2)}{j\omega C_1R_2}$$

Since $A_i=0$, we have $\mathbf{A}=A_r$

$$\therefore \qquad A_r=1+\frac{1-\omega^2C_1C_2R_1R_2}{j\omega C_1R_2}+\frac{C_1R_1+C_2R_2}{C_1R_2} \qquad \dots \qquad (9.53)$$

Equating the imaginary parts of both sides we get,

$$1-\omega^2 C_1 C_2 R_1 R_2=0$$

or, $$\omega^2=\frac{1}{C_1 C_2 R_1 R_2}$$

or, $$\omega=\frac{1}{\sqrt{C_1 C_2 R_1 R_2}}$$

$$\therefore \qquad f=\frac{1}{2\pi\sqrt{C_1 C_2 R_1 R_2}} \qquad \ldots \qquad (9.54)$$

Again equating the real part of both sides,

$$A_r=1+\frac{C_1R_1+C_2R_2}{C_1R_2}=1+\frac{R_1}{R_2}+\frac{C_2}{C_1}$$

If $R_1=R_2=R$, $C_1=C_2=C$, then

$$A_r=1+1+1=3$$

and $$f=\frac{1}{2\pi CR} \qquad \ldots \qquad (9.55)$$

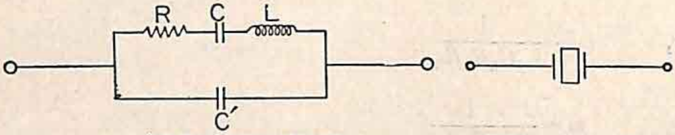
C_1, C_2 in the circuit are variable air capacitors having maximum to minimum capacitance ratio by about 10 : 1 and so according to equation (9.55) the frequency of the oscillator can be varied in the same ratio.

9.10 Crystal Oscillator

Some crystalline materials, e.g., quartz, show piezoelectric properties; that is they deform mechanically by the application of an electric field. Or, in other words when the crystal is deformed externally an electric potential is formed between the opposite faces of the crystal. This property of a quartz plate vibrates it mechanically when provided with conducting electrodes connected to an alternating voltage source. The vibrations produce electrical signals which are maximum at the natural mechanical resonant frequency of the crystal.

The electrical characteristics of a quartz crystal can be represented by the equivalent circuit shown in Fig. 9.9. In the figure the inductance L, capacitor C and the resistor R are all connected in series.

To this the electrostatic capacitance C' is added due to the parallel plate capacitance of the electrodes with the crystal as a dielectric.



(a) Equivalent Circuit (b) Circuit Symbol

Fig. 9.9

An RC oscillatory circuitt using quartz crystal is drawn in Fig. 9.10. The figure exhibits a simple form of 'Pierce Oscillator' employing the crystal. Basically, it is a Hartley oscillator where the cathode connection is made between the choke and the grid leak.

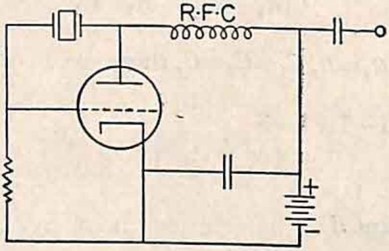


Fig. 9.10

Mathematically, we can express the motion of a vibrating body as,

$$m\frac{d^2x}{dt^2}+b\frac{dx}{dt}+kx=f(t) \qquad \cdots \qquad (9.56)$$

where, m=mass of the crystal,

b=internal mechanical loss coefficient

and k=elastic constant of the crystal.

As already mentioned, equation (9.56) is identical with the equation,

$$L\frac{d^2i}{dt^2}+R\frac{di}{dt}+\frac{1}{C}i=F(t) \qquad \cdots \qquad (9.57)$$

Since the two equations have identical form, mechanical resonance is expected. We therefore introduce a term mechanical Q factor, which can be written as,

$$Q=\frac{\omega m}{b} \qquad \cdots \qquad (9.58)$$

The series-parallel equivalent circuit of a crystal indicates a series resonant frequency ω_s (zero impedance) and a parallel resonant frequency ω_p (infinite impedance), where,

$$\omega_s = \frac{1}{\sqrt{LC}} \qquad \ldots \quad (9.59)$$

and $$\omega_p = \sqrt{1/L\left(\frac{1}{C}+\frac{1}{C'}\right)} \qquad \ldots \quad (9.60)$$

Accordingly the parallel resonant frequency is always higher than the series resonant frequency.

Crystal oscillators are widely used in cases where higher order of frequency stability is required. For such purposes quartz is almost universally used because it is highly strong and has a small temperature coefficient of expansion.

Examples

1. A tuned plate oscillator uses a vacuum tube having amplification factor $\mu=20$ and $g_m=10^{-3}$ mho. Inductance L of the tuned circuit is 50 mH and shunt capacitance including interelectrode and stray capacitances $C=160$ pF and resistance of 16 Ω. Find the frequency of oscillation of the circuit.

Here, $\mu=20$, $g_m=10^{-3}$ mho, $L=50$ mH$=50\times10^{-3}$ H,

$C=160$ pF$=160\times10^{-12}$ F . $R=16\ \Omega$.

The frequency of resonance f_R of the tuned circuit is given by,

$$f_R = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{50\times10^{-3}\times160\times10^{-12}}}$$

$$=56.28\times10^3 \text{ Hz}$$

$\therefore$ the frequency of oscillation,

$$f \simeq F_R\left(1+\frac{R}{2r_p}\right)$$

$$=56.28\times10^3\left(1+\frac{16}{2\times20\times10^3}\right) \left(\because \quad r_p=\frac{\mu}{g_m}=20\times10^3\ \Omega\right)$$

$$=56.30\times10^3 \text{ Hz}.$$

2. In a tuned grid oscillator the electron tube used has $\mu=15$ and $r_p=10\ \text{K}\Omega$. The resistance in the tuned circuit is 12 Ω and the tunning capacitance of 300 pF Find the mutual inductance between grid and anode coils for the maintenance of oscillation.

Here, $\mu=15,\ r_p=10\ \text{K}\Omega=10\times10^3\ \Omega,$

$R_1=12\ \Omega,\ C=300\ \text{pF}=300\times10^{-12}\ \text{F}.$

For the maintenance of oscillation,

$$g_m\simeq\frac{CR_1}{M}$$

or, $$M\simeq\frac{CR_1}{g_m}$$

Now, $$g_m=\frac{\mu}{r_p}=\frac{15}{10^4}=15\times10^{-4}$$

$$\therefore \quad M=\frac{300\times10^{-12}\times12}{15\times10^{-4}}$$

$$=2.4\times10^{-6}\ \text{H}.$$

Self-Test

Read each of the following and provide the appropriate words:

(a) An oscillator is used for converting — power into — power.

(b) The three different parts of an oscillator are the internal amplifier, feedback network and — limiting device.

(c) Microwave oscillators have frequency above — MHz.

(d) Sine wave oscillators are either negative resistance type or — type.

(c) Phase shift oscillators are — oscillators. (R–C/L–C).

(f) In tuned grid oscillator the tuned circuit is placed between grid and — and coupled to the — of the valve by mutual inductance.

(g) Crystal oscillators are widely used in cases where lower order of frequency stability is required. (True/False)

Review Questions

1. What is an oscillator? What are its essential parts?

2. How oscillators are classified? Discuss.

3. Show that for a tuned plate oscillator the frequency generated is slightly greater than the resonant frequency while for a tuned grid oscillator it is slightly less than the resonant frequency.

4. Discuss with circuit diagram the operation of a Hartley oscillator. Derive an expression for its frequency.

5. Sketch a Colpitts oscillator circuit and explain its action. What is the approximate frequency of oscillation?

6. Explain with necessary diagram a phase shift oscillator. Give its equivalent circuit. Find an expression for its frequency.

7. Sketch the circuit diagram of a Wien Bridge oscillator. Explain its action. Calculate an expression for its frequency.

8. What is a crystal oscillator? Why quartz is used for the purpose? With necessary diagram explain its action clearly. What are the uses of a crystal oscillator?

9. In a vacuum tube oscillator using a tuned anode circuit, the mutual inductance between the grid and the anode coils required is 3 mH. The tuned circuit has coil of inductance 50 mH and resistance of 16 ohms. Find the value of average mutual conductance for constant amplitude oscillation when the tuning capacitance in anode circuit is 160 pF. The vacuum tube used has $\mu=20$. (*Ans.* 5.02×10^{-6} mho)

CHAPTER 10

MODULATION AND DETECTION

10.1 Introduction

Our music or speech is usually in the form of low frequency waves lying in the audio frequency range of 0-15 kHz approximately which cannot be transmitted directly at a long distance. For transmission of intelligence or message from one place to another we have to take the help of high frequency or radio frequency waves. Such a process of raising the frequency of the intelligence or the message by superposition over a high frequency voltage is known as modulation. Or, briefly we may define modulation as a process of superposing information on a radio carrier wave. Thus it is seen that the process of modulation arose due to the human desire to establish communication over a long path. On the other hand, the reverse process of translating back the information from the radio wave to the original frequency is called demodulation or detection.

To illustrate the phenomena more explicitly let us consider the waveforms of Fig. 10.1. Here Fig. 10.1(a) reveals the electrical equivalent of a single musical tone which is simply an a.c. sine wave of the

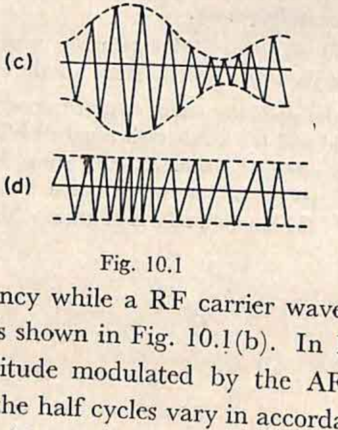


Fig. 10.1

corresponding frequency while a RF carrier wave of constant amplitude and frequency is shown in Fig. 10.1(b). In Fig. 10.1(c) the RF carrier is being amplitude modulated by the AF wave so that the amplitudes of both the half cycles vary in accordance with the audio signal. In (d) of Fig. 10.1 finally the frequency of the carrier is varied according to the amplitude of the AF signal. Note that if the positive amplitude of the audio wave is higher, the greater is the frequency of the RF carrier.

10.2 Types of Modulation

The equation of an alternating voltage may be accurately written as,

$$e = A_m \cos\theta \qquad \ldots \qquad (10.1)$$

where, A_m is the amplitude

and $\theta = \int \omega \, dt + \phi \quad \left(\because \text{ angular velocity } \omega = \frac{d\theta}{dt} \right)$

So we can writte equation (10.1) as,

$$e = A_m \cos\left(\int \omega \, dt + \phi \right) \qquad \ldots \qquad (10.2)$$

where the constant of integration ϕ is the phase angle.

Equation (10.2) clearly shows that the a.c. waves has two parameters which may be varied or modulated. These parameters are (i) the *amplitude* and (ii) the *angle*, causing the following two basic types of modulation:

(a) Variation of amplitude A_m with time, giving the amplitude modulation (AM).

(b) Variation of the angle with time, giving the angle modulation which has two subgroups, viz. (i) variation of $\int \omega \, dt$ with time resulting frequency modulation (FM) and (ii) variation of ϕ, the phase angle, with time resulting phase modulation (PM).

10.3 Analysis of Modulation

(a) Amplitude Modulation—For this case the angular velocity ω is a constant factor at ω_c, where ω_c is the so-called carrier frequency. Equation (10.2) can then be written as,

$$e = A_m \cos\left(\omega_c t + \phi \right) \qquad \ldots \qquad (10.3)$$

Let the signal or the modulating voltage is expressed as,

$$e_m = E_m \cos \omega_m t \qquad \ldots \qquad (10.4)$$

where, E_m is the amplitude and ω_m is the angular frequency of the signal.

Now, the amplitude A_m should vary as

$$A_m = E_c + K_a E_m \cos \omega_m t \qquad (K_a = \text{proportionality constant, } E_c = \text{amplitude of the carrier})$$

$$= E_c\left(1 + \frac{K_a E_m}{E_c} \cos \omega_m t\right)$$

$$= E_c\,(1 + m_a \cos \omega_m t) \qquad \ldots \qquad (10.5)$$

where, $m_a = \frac{K_a E_m}{E_c}$ is called the modulation factor and when multiplied by 100, it gives the percentage of modulation.

The complete expression for the amplitude modulated voltage is now written as,

$$e = E_c(1 + m_a \cos \omega_m t) \cos \omega_c t \qquad \ldots \qquad (10.6)$$

The constant phase term ϕ has been neglected here as it has no importance in this process.

(b) Frequency Modulation—For this case the angular velocity ω may be expressed as,

$$\omega = \omega_o + K_f E_m \cos \omega_m t \qquad \ldots \qquad \ldots \qquad (10.7)$$

where the centre frequency $f_o = \frac{\omega_o}{2\pi}$,

and K_f = degree of frequency variation.

Use of equation (10.2) then gives,

$$e = E_c \sin \int(\omega_o + K_f E_m \cos \omega_m t)dt + \phi$$

or, $$e = E_c \sin\left(\omega_o t + \frac{K_f E_m}{\omega_m} \sin \omega_m t\right) \qquad \ldots \qquad (10.8)$$

The integration constant ϕ is again dropped as a constant angle.

The frequency modulated voltage in equation (10.8) can alternately be written as,

$$e = E_c \sin\,(\omega_o t + \delta \sin \omega_m t) \qquad \ldots \qquad (10.9)$$

where, $\delta = \frac{K_f E_m}{\omega_m}$ is called the deviation ratio.

(c) Phase Modulation—For this case ω is a constant factor at ω_o. Equation (10.2) then gives the form

$$e = E_c \sin\,(\omega_o t + \psi) \qquad \ldots \qquad (10.10)$$

where the angle ψ may be given a time variation as,

$$\psi = \psi_o + K_p E_m \cos \omega_m t \quad \ldots \quad (10.11)$$

Here K_p relates the phase angle variation with the signal amplitude and is called proportionality constant.

From equation (10.10) substituting the value of ψ we have,

$$e = E_c \sin (\omega_o t + \psi_o + K_p E_m \cos \omega_m t) \quad \ldots \quad (10.12)$$

Neglecting the constant phase angle ψ_o, the general expression for a phase-modulated voltage is written as,

$$e = E_c \sin (\omega_o t + \psi_d \cos \omega_m t) \quad \ldots \quad (10.13)$$

In equation (10.13), $\psi_d = K_p E_m$ is called the phase deviation. It is interesting to note that the expressions for frequency and phase modulations obtained in equations (10.9) and (10.13) differ in the coefficients δ and ψ_d and also in a 90° shift in the modulation phase angle.

10.4 Sidebands and Energy Consideration

Both amplitude and frequency modulation systems serve well the basic function of communication. However, AM is more widely used due to its greater power output, simplicity of operation, etc., we shall here confine our attention only to the case of amplitude modulation.

We have found that the equation for an amplitude modulated wave may be written as,

$$e = E_c (1 + m_a \cos \omega_m t) \cos \omega_c t$$

where, $\cos \omega_m t \cos \omega_c t = \frac{1}{2} [\cos (\omega_c + \omega_m) t + \cos (\omega_c - \omega_m) t]$

$$\therefore \; e = E_c \cos \omega_c t + \frac{m_a E_c}{2} [\cos (\omega_c + \omega_m) t + \cos (\omega_c - \omega_m) t] \quad \ldots \quad (10.14)$$

Equation (10.14) shows that in an amplitude modulated wave there are altogether three frequencies. The first one is the original carrier frequency ω_c while the other two are the algebraic sum and difference of the carrier and modulation frequencies known as the upper side frequency and lower side frequency respectively. The width $\Delta\omega$ of the modulated wave is therefore given by,

$$\begin{aligned} \Delta\omega &= (\omega_c + \omega_m) - (\omega_c - \omega_m) \\ &= 2\,\omega_m \quad \ldots \quad (10.15) \end{aligned}$$

Thus we see that the required bandwidth for transmission of an amplitude modulated signal is twice the highest modulating frequency.

Again from equation (10.14) it appears that for both the sidebands the amplitude is $m_a/2$ times the carrier amplitude. Since power is directly proportional to the square of the voltage, we have,

$$\text{carrier power} = \frac{KE_c^2}{2} = P_c$$

$$\text{and total sideband power} = 2\ \frac{Km_a^2E_c^2}{8}$$

$$= \text{carrier power} \times \frac{m_a^2}{2}$$

$\therefore$ total power in a modulated wave

$$= \text{carrier power} + \text{total sideband power}$$

$$= \frac{KE_c^2}{2}\left(1 + \frac{m_a^2}{2}\right)$$

$$= P_c\left(1 + \frac{m_a^2}{2}\right) \qquad \ldots \quad (10.16)$$

10.5 Modulators

In order to get the amplitude modulation of a radio carrier, the modulating signal is injected into the RF power amplifier stages of a transmitter. There are several circuits for this purpose such as (i) *plate circuit modulation*, (ii) *control or screen or suppressor grid circuit modulation*, etc. Of these plate circuit modulation as discussed below is most commonly used because of its higher efficiency and simplicity in adjustment.

The fundamental circuit for plate modulation is shown in Fig. 10.2. Here the RF carrier is inserted to the grid point of a tuned RF

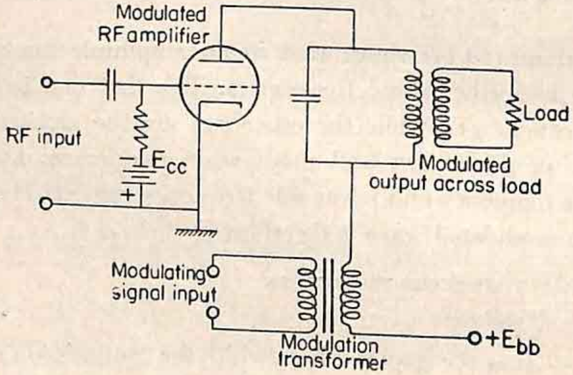


Fig. 10.2

amplifier stage while the AF modulating signal is injected in series with the d.c. plate supply. Now during the positive half cycle of the audio signal a positive voltage is induced in the transformer secondary causing an increase of RF voltage across the tank circuit while during the negative half the voltage induced in the secondary subtracts from the plate supply voltage and thus resulting a decrease of the RF voltage across the tank. In this fashion the amplitude of the plate circuit is altered with the audio signal and the modulated carrier appears in the secondary of the RF output transformer. To obtain 100 percent modulation the peak amplitude of the audio signal is made equal to the plate supply voltage.

10.6 Types of Detection

By detection, also known as demodulation, the audio component of a modulated wave is separated from the RF carrier component. Devices used for detection are called detectors which are classified into two categories: (a) *linear diode detectors* and (b) *square law detectors*. In linear diode detectors a linear relation exists between the carrier amplitude and the detected output voltage while a square law detector utilizes the non-linear portion of the dynamic current voltage characteristic. Since in the latter type, current flows continuously through the detecting circuit element, its behaviour can be analyzed easily using the power series representation.

Square law detectors of the following types are generally used: (a) *diode detectors* and (b) *triode detectors*.

10.6.1 Diode Detectors

These detectors are widely used in radio receivers as they are comparatively free from distortion and also very suitable for the automatic volume control.

The fundamental circuit diagram and waveforms of a diode detector are shown in Fig. 10.3. It is seen that the RF modulated signal is coupled here to the plate of the diode through a transformer. When the plate is positive with respect to the cathode the tube conducts and consequently a pulse of current flows through the tube and the load resistor R_L. But during the negative half cycle of the carrier signal no current flows. Thus at the output of the diode a series of positive half cycles of the carrier wave are obtained which, however, become much fast to be made audible in a speaker. To smooth out the remaining RF carrier variations a filter circuit consisting of a capacitor C and a load resistor R_L is used. The capacitor C bypasses all RF components while the average components develop a voltage across R_L and thus producing the desired detected output.

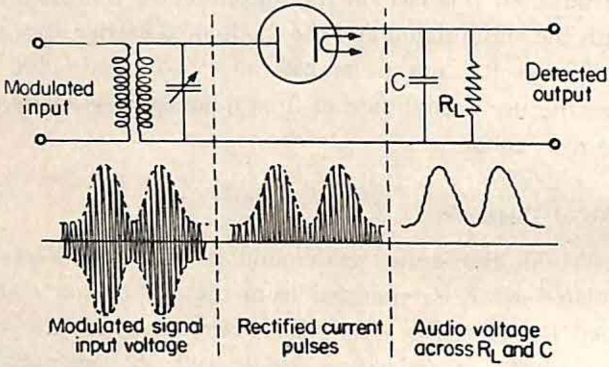

Modulated input
C
R_L
Detected output
Modulated signal input voltage
Rectified current pulses
Audio voltage across R_L and C

Fig. 10.3

Since the dynamic current voltage characteristic follows the square law relation we may write,

a.c. plate current $i_p = a_1 e_p + a_2 e_p^2$ ... (10.17)

and the plate voltage $e_p = E_c\,(1 + m_a \cos \omega_m t) \cos \omega_c t$ ... (10.18)

Obviously, the second term on the right hand side of equation (10.18) provides terms in frequencies ω_m, $2\omega_m$, $2\omega_c$, $2(\omega_c + \omega_m)$ and $2(\omega_c - \omega_m)$. The RF terms are bypassed by using high value capacitor while the terms in frequencies ω_m, $2\omega_m$ are formed across R_L. Out of these the term in frequency $2\omega_m$ is the distortion term while ω_m constitutes the desired output.

10.6.2 Triode Detectors

Square law triode detectors are of the following two types: (i) *anode bend detectors* and (ii) *grid leak detectors*.

The circuit diagram of the anode bend detector is shown in Fig. 10.4. The triode is biased heavily near the cut-off value so that the operation takes place near the non-linear portion of the transfer characteristic. Here also the RF components are bypassed by the capacitor C so that only the low frequency components are developed across the load resistor R_L. One great advantage of this circuit is that it amplifies the incoming signal besides the detection.

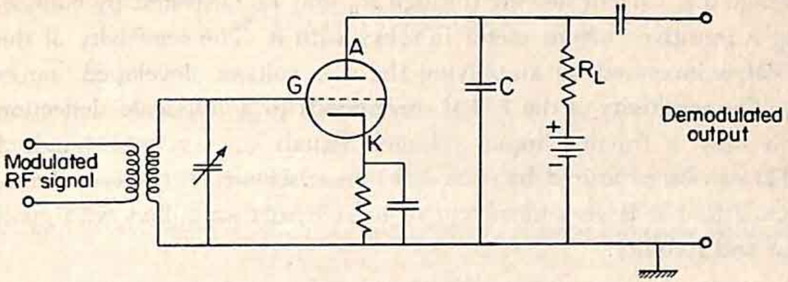


Fig. 10.4

A circuit diagram of a grid leak detector is shown in Fig. 10.5. Here the grid bias is set up by d.c. rectified current passing through R_g and the AF voltage across C_gR_g combination is amplified. Detectors of this type are not very sensitive and a strong signal voltage is required for their proper operation. There use is, therefore, limited mainly to the highly sensitive superheterodyne receivers.

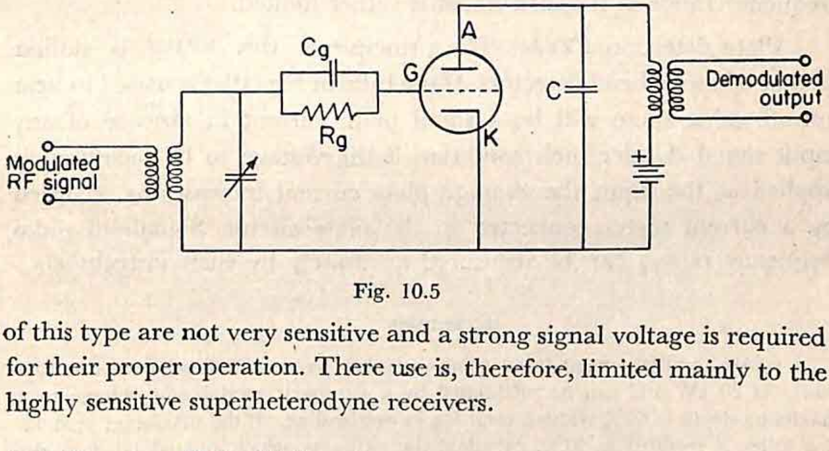


Fig. 10.5

10.7 Vacuum Tube Voltmeters

Vacuum tube voltmeter, abbreviated as *VTVM*, is a very valuable instrument to measure precisely voltages from very low audio frequencies to radio frequencies of few hundred MHz. This is achieved conveniently by using vacuum tube detectors and depending on the type of detectors used they can be broadly classified as: (a) *diode VTVM* and (b) *plate detection type VTVM*.

Diode *VTVM*—Diode *VTVM*s are usually available in two forms. (i) *peak indicating type* and (ii) *amplifier-rectifier average reading type*.

In the peak indicating type *VTVM*, similar to the diode detector shown in Fig. 10.3, the rectified d.c. voltage across CR_L combination is a measure of the peak amplitude of the input signal voltage. The average d.c. current flowing through R_L may be measured by connecting a sensitive current meter in series with it. The sensitivity of the *VTVM* is increased by amplifying the d.c. voltage developed across R_L. The sensitivity of the *VTVM* corresponds to a full scale deflection with only a fraction input voltage. Signals upto several hundred MHz can be measured by such instrument. However, the only drawback is that it is very inconvenient to construct amplifiers with good gain and stability.

In the average reading type *VTVM* the a.c. signal to be measured is first applied and then it is rectified. The output thus obtained becomes proportional to the average amplitude of the signal and hence it is so named. The sensitivity of the *VTVM* depends on the gain of the amplifier which is stabilized by making negative feedback. The frequency range of the instrument is rather limited.

Plate detection *VTVM*—The principle of this *VTVM* is similar to that of anode bend detectors. If the tube in Fig. 10.4 is biased to near cut-off value there will be a small plate current in absence of any input signal. Under such condition if the voltage to be measured is applied at the input the average plate current increases as recorded by a current meter connected in the plate circuit. Signals of radio frequency ranges can be measured accurately by such instruments.

Examples

1. An amplitude modulated transmitter has an unmodulated carrier output power of 20 kW and can be modulated by a sinusoidal modulating voltage to a maximum depth of 60% without resulting in overloading. If the maximum modulation index is rectified to 40%, calculate the value to which unmodulated carrier power may be increased without causing overloading.

We have,

modulated carrier power $P=P_c\left(1+\frac{m_a^2}{2}\right)$

Here, $P_c=20$ kW, $m_a=60\%$

So the maximum power which may be handled by the transmitter is,

$$P=20\left[1+\frac{(0.6)^2}{2}\right]=23.6$$

The increased unmodulated carrier power is then given by,

$$23.6 = P_c' \left[1 + \frac{(0.4)^2}{2}\right] = P_c' \times 1.08$$

$$\therefore \quad P_c' = \frac{23.6}{1.08} = 21.85 \text{ kW}.$$

2. A sinusoidal carrier voltage of amplitude 80 volts and frequency 1 MHz is amplitude modulated by a sinusoidal voltage of frequency 10 kHz producing 40% modulation. Determine the frequency and amplitude of lower and upper sidebands.

Frequency of lower side band $= 1 \text{ MHz} - 10 \text{ kHz}$

$= (1000 - 10) \text{ kHz}$

$= 990 \text{ kHz}$

Frequency of upper side band $= 1 \text{ MHz} + 10 \text{ kHz}$

$= (1000 + 10) \text{ kHz}$

$= 1010 \text{ kHz}$

Amplitude of both the side bands

$$= \frac{m_a E_c}{2}$$

$$= \frac{0.4}{2} \cdot 80 \quad (\because \ m_a = 0.4, \ E_c = 80 \text{ volts})$$

$$= 16 \text{ volts.}$$

Self-Test

Read each of the following and provide the appropriate words:

(a) — may be defined as a process of superposing information on a radio carrier wave.

(b) If the positive amplitude of the audio wave is higher, the — is the frequency of the RF carrier. (smaller/greater).

(c) The expressions for frequency and phase modulations differ in a — degree shift in the modulation phase angle.

(d) In an amplitude modulated wave there are altogether three frequencies; known as original — frequency, the upper side frequency and the — side frequency.

(e) The required bandwidth for transmission of an amplitude modulated signal is — the highest modulating frequency.

(f) Devices used for detection are called —.

(g) The use of grid leak detector is mainly limited to the highly sensitive — receivers.

(h) Signals of radio, frequency ranges can be measured accurately by — — VTVM.

Review Questions

1. Explain with suitable diagrams what is meant by modulation and demodulation.

2. What are the different types of modulation? Clearly define those.

3. Find expressions for amplitude, frequency and phase modulations.

4. Show that an amplitude modulated wave can be represented by a carrier and two sideband frequencies for each frequency of modulation.

5. Find an expression for the total power in a modulated wave.

6. What are modulators? Describe briefly the principle of plate circuit modulation.

7. Discuss briefly with necessary circuit diagrams the following:
(a) Diode Detectors (b) Triode Detectors.

8. Write a short note on vacuum tube voltmeters.

9. A modulating voltage of 1000 Hz frequency is used to frequency modulate a carrier of 100 kHz so as to produce a frequency deviation of 25 kHz. Calculate the modulation index and band width of the modulated wave. (*Ans.* 25, 50 kHz)

10. A sinusoidal carrier voltage of frequency 800 kHz and amplitude 120 volts is amplitude modulated by a sinusoidal frequency 20 kHz producing 60% modulation. Calculate the amplitude and frequency of lower and upper sidebands.
(*Ans.* 36 volts; 780 kHz, 820 kHz)

11. A carrier wave of 1000 kHz frequency and of 100 volts amplitude is 80% modulated by a modulating voltage of 1 kHz frequency. Find the frequencies and the amplitude of the sidebands. Calculate also the proportions of powers present in the carrier and in the sidebands. (*Ans.* 999 kHz, 1001 kHz; 40 V; 1 : 1.6)

CHAPTER 11

RADIO COMMUNICATION

11.1 Introduction

In 1865, Prof. C. Maxwell, an English scientist, first predicted the existence of the electromagnetic (radio) waves which was later verified by a German scientist H. Hertz in 1887 using a simple transmitter and a detector. A more sophisticated communication system for a distance of about 2 miles sent out the first radio telegraphy messages in 1896. Continued research on the science of radio communication system was started from 1901 but the progress was very slow and erratic until the invention of the crystal detector and the triode valve by Lee De Forest in 1907.

Present radio communication system consists of either modulation of radio waves by speech or music, called radio telephony, or continuous radio waves (CW) with a telegraphic code, known as radio telegraphy.

The basic elements of a radio communication system are shown in Fig. 11.1. The elements are: (i) *a microphone* or *a telegraph key* to control the radio waves, (ii) *a transmitter* for generation of radio waves, (iii) *a transmitting antenna* and *a receiving antenna*, (iv) *a radio receiver* to select, amplify and demodulate the information present in radio waves and (v) *a loudspeaker* or *a headphone* to convert the electrical waves into *sound*.

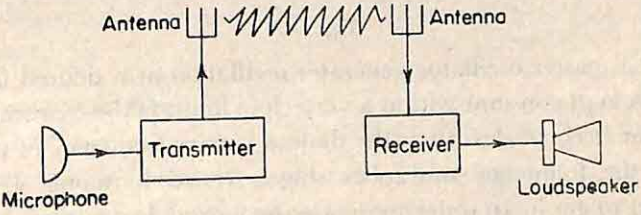


Fig. 11.1

11.2 Radio Transmitters

Radio transmitters may be broadly classified according to the (a) *type of modulation used*, (b) *the carrier frequency involved* and (c) *the service processes involved.*

According to modulation—There are amplitude, frequency and phase modulation transmitters.

According to carrier frequency—Long, medium and short wave transmitters, VHF and UHF transmitters and microwave transmitters.

According to service processes—Radio broadcast, radio telephone and telegraph, television, radar and navigational transmitters.

11.2.1 AM Radio Transmitter

An AM radio transmitter using modulation at high carrier power level is discussed here briefly.

A block diagram of the transmitter is given in Fig. 11.2, which consists essentially (i) *a master oscillator*, (ii) *a number of frequency multipliers*, (iii) *several power amplifiers* and (iv) *modulating system.*

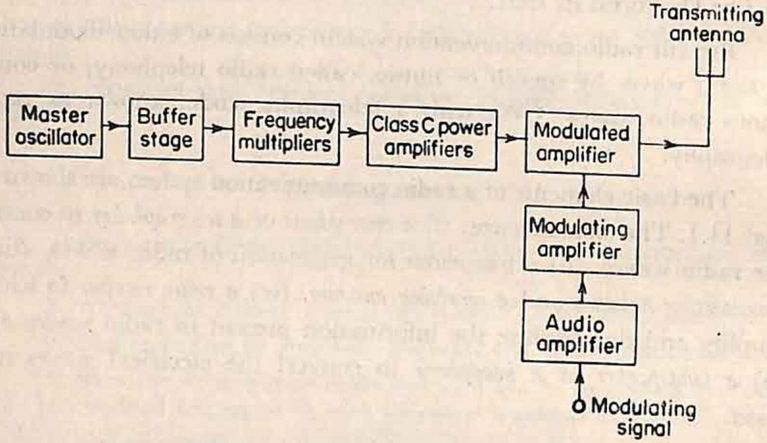


Fig. 11.2

The master oscillator generates oscillation at a desired frequency which is kept constant within a very close limit. If the frequency of the oscillator becomes less than the desired carrier frequency of the transmitter the frequency multiplier stages, called harmonic generators, are used to get it. In order to isolate the harmonic generators from the master oscillator a buffer stage is used as shown, so that the variation of load, if any, may not affect the oscillator.

The RF voltage thus generated by the oscillator has a low power which is raised to a sufficiently high value by a chain of class C amplifiers and is then modulated by using usually series plate modulation of high efficiency. At low power levels, however, grid bias modulation and suppressor grid modulation are also used sometimes.

The modulating amplifiers, generally a class B pushpull type, feeds audio power into the modulated amplifier which is finally connected to the transmitting antenna, as shown.

11.3 Antenna

We have already seen that in order to radiate or receive electromagnetic waves successfully an antenna is required. The antenna, popularly known as aerial, is a system of elevated conductors. A transmitting antenna radiates power from a transmitter in all directions or in some definite directions while a receiving antenna intercepts a part of that electromagnetic energy travelling through the atmosphere.

From the famous Maxwell's theory we know that the accelerated electric charges (i.e., electrons) always radiate energy in the form of electromagnetic waves whose electric and magnetic fields travel at right angles to each other. The orientation of the electric field with respect to earth is called polarisation. Accordingly if the plane of the electric field is oriented horizontally it is said to be horizontally polarised while if the field is vertical with respect to earth, the wave is said to be vertically polarised. Obviously the wave polarisation is basically a function of the antenna orientation.

11.4 Receiving Antenna

In principle, the design and shape of both the transmitting and receiving antennas are same. However, because of space restrictions, the receiving antenna has usually a convenient length or loop of wire in practice.

11.4.1 Characteristics

Characteristics of an ideal receiving antenna are : (i) it receives all the desired signal efficiently, (ii) it has an omnidirectional characteristic for long, medium and short wave receptions while for VHF and UHF reception directional properties are utilized, (iii) with change of signal frequency, it has small variation of terminal impedance and (iv) it should minimise interference effect due to house wiring, etc. and also fading characteristics.

11.4.2 Classification

The receiving aerials may be either indoor or outdoor type. The indoor aerial has a comparatively poor pick up and its terminal impedance has large resistive and capacitive components. The outdoor aerials are of the following types: (a) *vertical aerial*, (b) *inverted-L aerial*, (c) *T-aerial* and (d) *dipole aerial*.

Vertical aerial—It is easy to construct. This aerial receives only vertically polarised transmission and so minimizes distortion and fading which may be caused by obliquely, circularly or elliptically polarised transmission. Hence for reception of medium and long waves it is often preferred to inverted-L aerial.

Inverted-L aerial—It has a long horizontal top with a vertical lead-in wire. The horizontal top influences both the terminal impedance and total induced voltage in the aerial. The horizontal portion also adds a capacitance between the top of the vertical section and the earth. This capacitance for a vertically polarised incident wave becomes more effective for the voltage induced in the vertical section.

The disadvantage of the aerial is that it collects both horizontally and vertically polarised components of the incident electromagnetic wave. The components, as a result, get a random phase relation and so tend to cause distortion and fading.

T-aerial--The operation of the T-aerial is little different from that of an inverted-L aerial. The horizontal section, divided into two parts, in a T-aerial serves as a capacitor to earth and thus increases the effective height. The balanced horizontal top is used to cancel the horizontally polarised wave coming at right angles to the aerial top. As far as other directions are concerned the horizontally polarised wave will provide sufficiently less pick up in comparison to an inverted-L aerial.

It is to be noted that both the T- and inverted-L aerials are used mainly for medium and long wave reception but are not suitable enough for short waves. At short wave reception when the aerial length becomes approximately $\lambda/4$ it forms resonance which causes serious mistuning and damping in the first tuned circuit.

Dipole aerial—The dipole aerial consists of two equal lengths of open wire connected to the receiver by a feeder. The two wires are at 180° with each other and they are kept in the same plane.

Reflectors and directors may be used in a dipole aerial to increase the directivity. The reflector is made slightly longer than the dipole and is usually spaced $\lambda/4$ from the dipole and parallel while the director is made slightly shorter than the dipole and spaced $\lambda/8$ apart and parallel.

To increase the impedance of the dipole, it is folded. A folded dipole, in fact, has an impedance four times greater than that of a simple dipole.

The aerial described above is very useful for short wave reception. Since in a short wave communication the radio waves coming from the ionosphere has an appreciable horizontally polarised components which induces the desired voltage in the horizontal dipole. Besides, when erected horizontally the aerial is balanced to earth and so cancelling the local interference effect.

11.5 Propagation of Electromagnetic Waves

We know that the radio frequency energy in the form of electromagnetic waves travels outward from a transmitting antenna with a velocity of 1,86,000 miles per second. These waves can easily penetrate non-metallic objects but are little influenced by the disturbed weather like rain, snow, etc. They are supposed to travel best in a free space or in a vacuum and no medium is necessary for its propagation.

Several ways are there for the propagation of electromagnetic waves from a transmitting to a receiving antenna. The most important of these are: (i) *ground or surface wave*, (ii) *space or tropospheric wave* and (iii) *sky wave*.

In ground wave propagation the electromagnetic waves are guided by the surface of the earth and follow a curved surface from the transmitting to the receiving antenna. Obviously the propagation in this case is controlled by the radio frequency characteristics of the ground like conductivity, dielectric constant, etc. Ground wave propagation is utilized suitably in the MF band (300 kHz–3000 kHz) where field intensities are obtained upto a distance of few hundred miles and the vertical antenna radiates in all directions equally. So this wave has practical importance for local radio broadcasts.

In space wave propagation the e.m. waves travel within the first 10 miles over the earth's surface, i.e. in the earth's troposphere either directly through the space or after reflection from the ground. Space wave propagation becomes important in the VHF band from 30 MHz.

With contributions from the ground reflected wave, TV and FM signals are transmitted in this way. UHF transmission also takes place by utilizing the space wave.

In sky wave propagation the e.m. waves come to the receiving antenna by reflection from the ionised upper atmosphere known as ionosphere. Obviously the propagation in this case is controlled by the reflecting property of the ionised upper atmosphere which has erratic changes with night and day atmospheric conditions and seasons. The sky wave propagation is the primary method of short wave communication around the world.

11.5.1 The Ionosphere

It is well known by now that the layers of ionised particles, called collectively as the ionosphere, are created due to various strong radiations coming from the sun. During day time both electrons and ions are formed at different heights about 60 km above the ground while at night they recombine. In Fig. 11.3, the variations of electron density with height at day and night time are shown by solid and dotted lines respectively. The figure shows that during day time D, E, F_1, and F_2 layers are formed while at night the D layer is absent and the F_1 and F_2 layers merge together to create a night time F layer. Above the F_2 layer the electron density decreases exponentially with height, as shown.

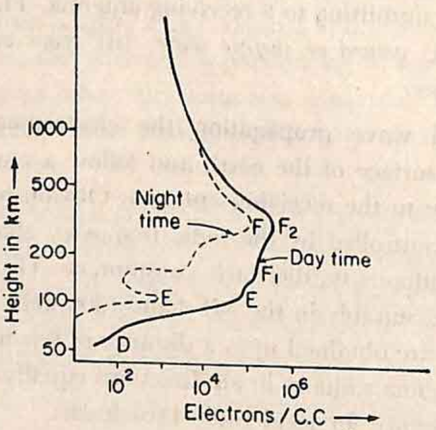


Fig. 11.3

The maximum electron densities and the corresponding heights of different ionospheric layers are required to know for a successful design of the communication link. A close observation of Fig. 11.3 reveals that during day time D and E layers are situated at 60 and 100 kms respectively whose corresponding electron densities are 10^4 and 10^5 electrons/c.c. The height of the F_1 layer is about 200 kms with an electron density of twice the E layer, while the F_2 layer is situated at about 300 kms with a maximum electron density of 10^6 electrons/c.c. At night the electron density of the E layer decreases by a factor of 10 from its day time value. For the F layer also which is formed by the combination of F_1 and F_2 layers at such times it decreases by the same factor from the value of the F_2 layer.

11.5.2 Basic Equation of Electromagnetic Wave

Let us consider after Eccles and Larmor the basic equation of an electromagnetic wave that travels through an ionised medium containing N electrons per c.c. each of charge e and m. We shall neglect here the effect of collision and also assume the absence of any external magnetic field.

Let the electric field of fluctuating intensity associated with the e.m. wave is,

$$E=E_0 \sin \omega t$$

$$=E_0 \sin 2\pi f t \quad (\because \text{ angular frequency, } \omega=2\pi f) \qquad (11.1)$$

where, E_0 is the amplitude of the wave and f is its frequency.

The electron will vibrate under the action of the electric field whose equation of motion is,

$$m\frac{dv}{dt}=E_0\, e \sin 2\pi f t$$

Integrating,

$$v=-\frac{E_0\, e}{2\pi m f}\cos 2\pi f t \qquad \cdots \qquad (11.2)$$

where the constant of integration is made zero by a proper choice of the phase.

The motion of electrons produces a convection current I_c and a displacement current I_d, where,

$$I_c=Ne\, v$$

$$=-\frac{E_0\, N e^2}{2\pi m f}\cos 2\pi f t \qquad \cdots \qquad (11.3)$$

and $I_d = \frac{K}{4\pi} \cdot \frac{dE}{dt}$ (K=dielectric constant of the medium)

$$= \frac{KE_o}{4\pi} \cdot 2\pi f \cos 2\pi f t = \frac{KE_o}{2} f \cos 2\pi f t \quad \dots \quad (11.4)$$

$\therefore$ the total current, $I_t = I_c + I_d$

$$= \left(K - \frac{N e^2}{\pi m f^2}\right) \frac{E_o f}{2} \cos 2\pi f t \quad \dots \quad (11.5)$$

The effect of the electrons thus reduces the dielectric constant from K to $\left(K - \frac{N e^2}{\pi m f^2}\right)$ or in empty space from unity to $\left(1 - \frac{N e^2}{\pi m f^2}\right)$ and alters the phase velocity v_p from the free space velocity c by,

$$v_p = \frac{c}{\sqrt{1 - \frac{N e^2}{\pi m f^2}}} \quad \dots \quad (11.6)$$

The refractive index of the ionised layer is then given by,

$$\mu = \frac{c}{v_p} = \sqrt{1 - \frac{N e^2}{\pi m f^2}} \quad \dots \quad (11.7)$$

If the wave is incident vertically on the ionised layer, then the angle of incidence $\phi_o = 0$ and so the condition of total reflection is

$$\sin \phi_o = \sin 0 = 0 = \sqrt{1 - \frac{N e^2}{\pi m f^2}}$$

or, $N = \frac{\pi m f^2}{e^2}$

$$= (1.24 \times 10^4) f^2 \text{ electrons/c.c.} \quad \dots \quad (11.8)$$

Next, in order to explain the 'skip distance' and the 'maximum usable frequency', let us consider Fig. 11.4 where ray paths have drawn for different angle of incidence ϕ_o. When ϕ_o is relatively large (ray 1), the condition $\mu = \sin \phi_o$ is satisfied and the refractive index becomes slightly less than unity. Under such conditions the wave returns to earth after slight penetration of the ionised layer. But as ϕ_o is decreased more and more (rays 2, 3 and 4), λ must be progressively smaller to return the wave and the penetration into the layer will be deeper. With further decrease of ϕ_o, the maximum electron density will be unable to reflect the wave and thus penetration occurs (rays 5, 6).

Therefore we see that as ϕ_o decreases, the distance from the transmitter to the point where a ray returns to the ground first decreases (rays, 1, 2) until we arrive at the angle of incidence ϕ_o at which the distance becomes minimum (ray 3). This distance is called the 'skip distance' and the corresponding frequency of the sky wave is termed as the 'maximum usable frequency' (MUF). An ionospheric layer will therefore be unable to return a sky wave if the frequency of transmission becomes greater than the maximum usable frequency for that receiving point.

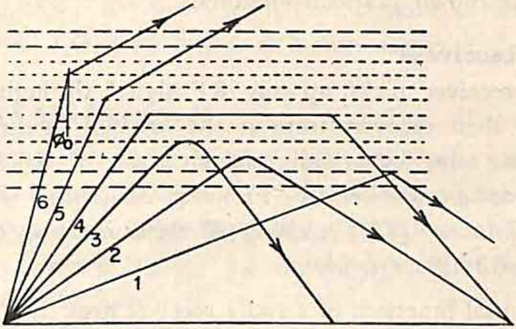


Fig. 11.4

11.5.3 Fading

The signals received by a radio receiver depend on the ionospheric characteristics which is again influenced by night and day, seasons of the year and atmospheric conditions. The intensity of any signal coming after reflections from the ionosphere is often fluctuating in nature. The phenomenon of fluctuating field intensity is called fading. Fading is mostly occurred on short wave band but also noticed sometimes on higher bands. The fluctuations in signal strength at a receiver may be due to several reasons.

(i) Fading may occur on short wave band when radio waves after reflections from the ionospheric layers reach at a common receiving point. The field strength at the receiver at such times is the vector sum of the field intensities by the two rays. Most severe fading is noticed when the component intensities are of the same order.

(ii) Fading may occur due to interference between the direct ground wave and the indirect reflected wave received simultaneously at the receiver.

(iii) Since the variation in the length of the ray path through the ionosphere is a function of frequency, the carrier wave and the sideband components may combine differently causing a frequency distortion. This is known as selective fading.

11.6 Radio Receivers

A radio receiver picks up any RF signal through a receiving antenna and then recovers from it the original modulating signal. Radio receivers may be broadly classified as: (a) *Amplitude Modulation* (AM) *broadcast receivers*, (b) *Frequency Modulation* (FM) *broadcast receivers*, (c) *Television* (TV) *receivers*, (d) *Radar receivers*, (e) *Communication receivers* and (f) *Code receivers*.

The essential functions of a radio receiver are: (i) To extract the desired RF signal from the electromagnetic waves, (ii) to amplify the RF signal, (iii) to demodulate the RF signal for getting back the original modulating voltage and (iv) to feed the modulating voltage in an indicator, like loudspeaker, etc., for receiving the original programme.

11.6.1 Broadcast Receivers

Both AM and FM broadcast receivers are usually used in home for entertainment purposes. The following characteristics of a broadcast receiver are of primary importance.

(i) Adaptibility to different aerials—A receiver is to be designed in such a manner so that it can be applied to any type of aerial.

(ii) Operational simplicity—Since broadcast receivers are used by listners with little technical knowledge, a simplicity of operation is desired. A receiver in its most elementary form, has therefore three controls. These are bandswitch, tuning control and volume control.

(iii) Good fidelity—Good fidelity of a receiver means a uniform frequency response over the entire audio frequency band. For an AM receiver the maximum modulating frequency is 5 kHz while for an FM receiver this is 15 kHz and so the latter gives a better fidelity.

(iv) Average sensitivity—The term sensitivity of a receiver is defined as the minimum input voltage necessary for producing a standard output voltage. A receiver should have reasonably high sensitivity to achieve good response over the low and medium strength signals. However, it should not be high enough since then it will pick up even the undesired disturbances.

(v) Good selectivity—By the term selectivity of a radio receiver is meant its ability to differentiate a desired signal of a particular frequency from other unwanted signals of slightly different in frequencies. Good selectivity depends on the sharpness of the resonance curves of different tuned circuits used in the receiver.

11.6.2 Types of AM Receivers

Depending on the techniques of operation radio receivers are classified into two types. These are: (i) *straight receivers*, which operate in a straight manner without frequency conversion and (ii) *superheterodyne receivers*, which convert AF signals to standard intermediate frequency before detection.

11.6.3 Straight Receivers

Let us first consider the operation of a simple crystal receiver which illustrates the basic principle of radio reception. A schematic diagram of the receiver is shown in Fig. 11.5. The electromagnetic waves radiated by the radio transmitters are picked up by the receiving antenna which is coupled to the L-C tank circuit through a step up RF transformer where some amplification takes place. The tank circuit serves the purpose of signal selection which is rectified by a crystal of silicon (or carborundum, etc.) for converting the oscillatory current into unidirectional current. Finally it acts on the diaphragm of the headphone and produces sound.

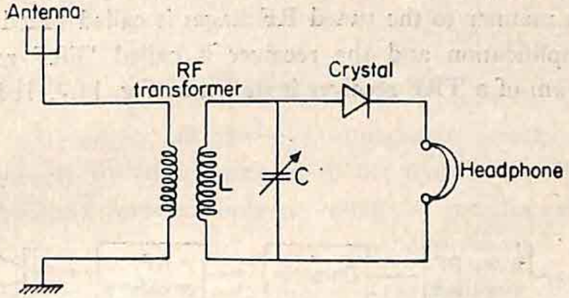


Fig. 11.5

The crystal receiver has drawbacks of poor sensitivity and selectivity. Improvement in sensitivity is made by substituting the crystal by a vacuum tube. A typical vacuum tube receiver of this type is shown in Fig. 11.6. The vacuum tube along with R_gC_g combination and bypass capacitor C_p removes the remaining RF components and keeps them out of the headphone. Though the sensitivity of this receiver is high enough but selectivity is considerably low which may be increased by using one or more tuned RF amplifier stages. Amplification in this manner to the tuned RF stages is called tuned radio frequency amplification and the receiver is called 'TRF receiver'. A block diagram of a TRF receiver is shown in Fig. 11.7. It has several stages of RF amplification with tuned tank circuit at the input of each stage, an AM detector and one or more AF amplifiers which finally connected to a loudspeaker. One major limitation here is that the selectivity of the receiver varies sufficiently with the variation of the signal frequency. With the increase of the frequency the selectivity is found to decrease. It may be noted that the TRF receiver though has enough selectivity but if too many tuned RF stages are used, the circuit becomes too selective and then reduces the fidelity of the receiver.

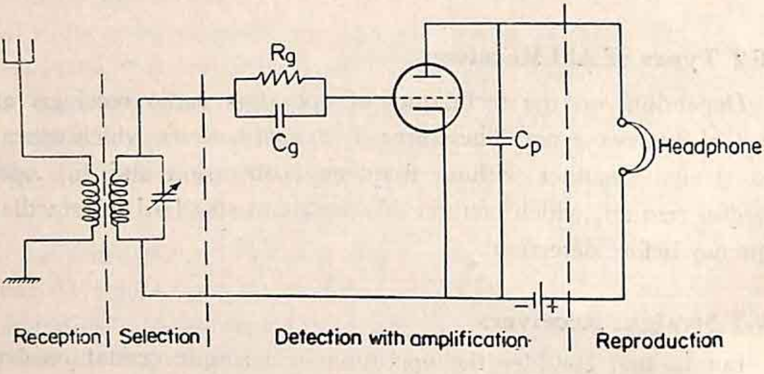


Fig. 11.6

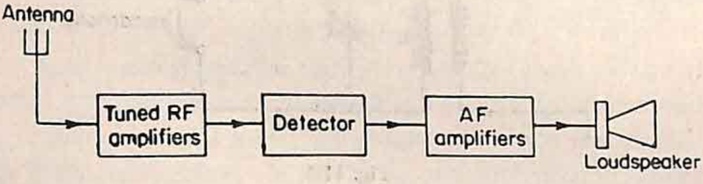


Fig. 11.7

11.6.4 Superheterodyne Receivers

Major Aramstrong invented the superheterodyne receiver during the First World War. In this receiver all incoming carrier frequencies are converted to a fixed lower value, called the intermediate frequency at which the amplifier circuits can operate with maximum stability, sensitivity and selectivity. Such conversion to the intermediate frequency (IF) is made by beating or heterodyning the carrier frequency against a locally generated frequency.

A block diagram of the basic superheterodyne circuit is shown in Fig. 11.8. Functions of different stages are discussed below.

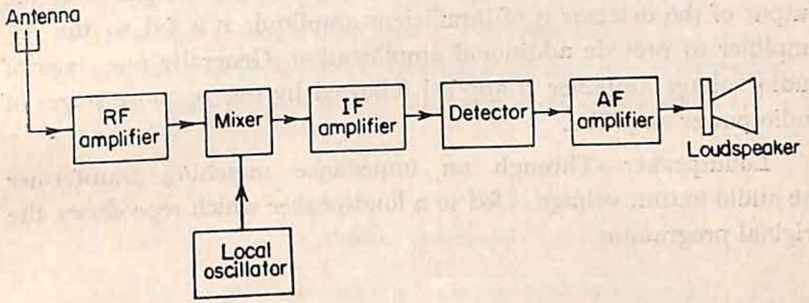


Fig. 11.8

Antenna—It receives all the electromagnetic waves and the voltages so induced are communicated to the receiver input where a parallel tuned circuit responds only to voltage at the desired carrier frequency.

RF Amplifier—The voltage developed across the capacitor of the input tuned circuit needs to amplify for detecting weak signals. This is done by one or two RF voltage amplifiers designed to amplify only narrow band of frequencies using tank circuits. By varying the capacitance or the inductance of the tank circuits the desired signal is selected and then amplified.

Mixer and Local Oscillator—In a superheterodyne receiver the carrier frequency f_c and the frequency of the local oscillations f_o are fed to a device called mixer, at the output of which a voltage of frequency $(f_c - f_o)$ is obtained. This frequency difference is known as the intermediate frequency (IF) and may be designated as f_i. The typical value of f_i is 456 kHz.

IF Amplifier—It consists of one or more stages of tuned voltage amplifier designed to amplify only a narrow band of frequencies around a fixed centre frequency. Since this centre frequency has a value intermediate between the radio and audio frequencies, the amplifier is designated as an IF amplifier. Most of the receiver amplifications and selectivity are provided by this IF amplifier.

Detector—Output of the IF amplifier is fed to the detector to separate the modulating signal from the carrier wave which was superposed at the transmitter. The detector is usually a linear diode detector the output of which gives the audio frequency signal.

AF Amplifier—Since the audio frequency signal obtained at the output of the detector is of insufficient amplitude it is fed to the AF amplifier to provide additional amplification. Generally one stage of audio voltage amplifier is applied followed by one or more stages of audio power amplifier.

Loudspeaker—Through an impedance matching transformer the audio output voltage is fed to a loudspeaker which reproduces the original programme.

Self-Test

Read each of the following and provide the appropriate words:

(a) Radio communication system consists of either modulation of radio waves by speech called — — or continuous radio waves with a telegraphic code called — —.

(b) If the field is vertical with respect to earth, the wave is said to be — —.

(c) In a dipole aerial the two wires at — degree with each other.

(d) In sky wave propagation the e.m. waves come to the receiving antenna by reflection from the —.

(e) At night D layer is present. (True/False)

(f) The electron density of the E layer is — electrons/c.c.

(g) If a TRF receiver becomes too selective it reduces the — of the receiver.

(h) In a superheterodyne receiver all incoming carrier frequencies are converted to a fixed lower value called the — —.

Review Questions

1. What are the basic elements of a radio communication system?

2. What are the different types of radio transmitter you know? With a block diagram briefly explain an AM radio transmitter.

3. What is an antenna? Mention the important characteristics of an ideal receiving antenna.

4. Explain briefly the following: (a) vertical aerial, (b) inverted-L aerial, (c) T-aerial and (d) dipole aerial.

5. How electromagnetic waves are propagated from a transmitting to a receiving antenna? Discuss briefly.

6. Write a note on the 'Ionosphere' explaining its different layers and the corresponding electron densities.

7. Establish the basic equation of electromagnetic wave. Explain what is meant by 'skip distance' and MUF?

8. How radio receivers can be classified? What are its essential functions? Mention the important characteristics of broadcast receivers.

9. Explain with circuit diagram the operation of a straight receiver. What are its limitations?

10. With a suitable block diagram discuss the different parts of a superheterodyne receiver.

CHAPTER 12

ELEMENTS OF TELEVISION AND RADAR

TELEVISION

12.1 Introduction

Throughout the history of human civilization, man has contrived in differend ways to extend his sense of sight. The microscope, the telescope and the camera were important landmarks along the way. These inventions were based upon an important characteristic of the human eye known as 'persistence of vision'. Television is one of those miracles which enables us to view a scene occurring at a far distance. By the word television we literally mean 'seeing at a distance' just as we have accepted long ago hearing at a distance.

12.2 Plan of Television System

A television system comprises a transmitter and a receiver. In the transmitter section a television camera breaks the image into tiny parts which after suitable processing fed to the transmitting antenna. The antenna then radiates the signal in the form of electromagnetic waves. These e.m. waves are received by the receiving antenna where they are fed to the television receiver to produce a visible image on the screen of the picture tube.

Fig. 12.1 is a simplified presentation of a television system that employs both AM picture transmitter and FM sound trnasmitter.

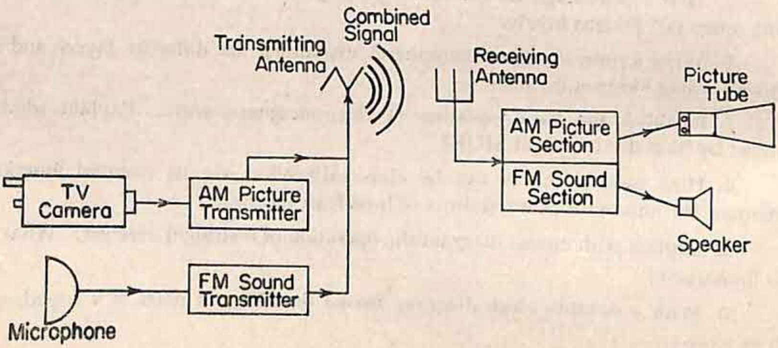


Fig. 12.1

By a single antenna the picture and sound signals are transmitted at different frequencies to avoid interference. These two signals are also received by a single antenna wherefrom they are separated by the AM picture section and FM sound section. The picture signal originating from TV camera terminates in a picture tube while the sound signal originating from microphone terminates in the speaker.

12.2.1 Picture Analysis

A picture is, in general, characterized by a distribution of light and shade over it. An area of an image whose size corresponds to the smallest detail and has a uniform total value is called the picture element. A complete picture consists of a large number of these tiny picture elements. So for transmitting a picture properly it is required to transmit the visual information of each picture element separately so that their respective identity is not lost at the receiving station. This is done suitably by using the phenomenon of photoelectricity which converts light energy into electrical signal. In practice, all the electrical impulses of the different picture elements are picked up one after another and then transmitted rapidly through a single channel. This process is called TV scanning. At the receiving end these impulses are converted into picture elements in the same sequence. Because of the rapid scanning and owing to 'persistence of vision' all the picture elements appear simultaneously before our eyes.

The scanning of the image can be done by a number of ways. Out of which the method of linear interlaced scanning is used widely now-a-days. In this method, the scanning beam goes over the series of slightly inclined lines downwards to the right. Schematic illustration of linear interlaced scanning is given in Fig. 12.2(a) and (b). Fig. 12.2(a) shows the downward movement of the scanning beam while the upward movement is shown by Fig. 12.2(b). These movements may be explained by going through the following steps:

(i) In Fig. 12.2(a), the scanning spot starts to move from *P*1 to the right hand point *Q* and then reversing its motion it comes quickly to *R*3 and proceeds so on upto the point *S*.

(ii) The upward movement of the spot now starts from *S*, as shown in Fig. 12.2(b), and comes at *U*, at the centre of the top line.

(iii) The downward movement of the spot further starts from *U*, as shown in Fig. 12.2(a) and it traverses the even number line such as 2, 4, 6, 8, etc. and ends at *V*.

(iv) At this stage, from the point *V* the scanning spot again traverses up and comes back to *P*.

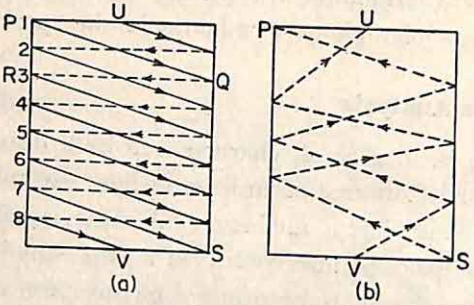


Fig. 12.2

The whole frame thus is accurately scanned using two sets of scanning lines. The interlacing of the scanning lines reduces considerably the flickering of the image.

In actual cases, the number of lines per picture frame varies from one system to another. A typical value is 525 lines per picture frame so that there are alternate pairs of 262.5 lines constituting a field. The entire picture is scanned about 25 to 30 times per second depending on the frequency of the power supply.

TV Camera (Pick-up device): The function of the TV camera is to generate electrical signals suitable for each picture element and to scan the image in proper sequence. A typical TV camera known as iconoscope is shown in Fig. 12.3. Its action can be explained as follows:

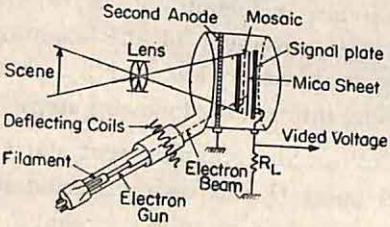


Fig. 12.3

Light from an illuminated scene, as shown by arrow mark, is made to focus by optical lenses on a photosensitive mosaic screen. The mosaic is a coating of millions of light sensitive gloubles each about 0.001 inch in size and is insulated well by using a mica sheet. At the other side of the mica sheet there is a conducting signal plate coated with a film of graphite. The gloubles insulated by the mica from the metallic coating thus form tiny electric capacitors with a mica dielectric and the common metallic signal plate. Therefore in accordance with the intensity of the light, electrons are emitted from each glouble and thereby charges up its individual capacitor.

The stored electrical image on the mosaic cannot be transmitted as a whole. For this a sharply focussed electron beam formed by the electron gun in the narrow elbow of the tube is made to scan the mosaic through the attraction of the highly positive second anode, called the collector ring. The beam neutralizes successfully the previous positive charge formed by photo emission and as a consequence discharges the glouble capacitor. At that instant a voltage generates across the load resistor R_L connected to the signal plate. The amplitude of this voltage varies with the light intensity of the corresponding picture element and it is known as picture signal.

It is to be noted in this connection that the TV camera of iconoscope type, described above, has a low video output and so it has been replaced by 'image orthicon' or 'vidicon' camera tubes which are much sensitive and can televise anything visible with naked eye.

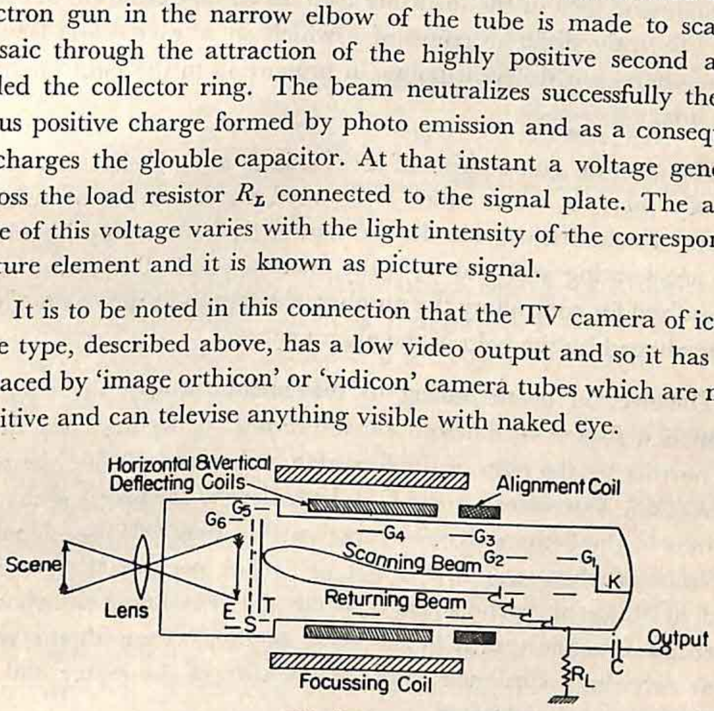


Fig. 12.4

Image orthicon: The television camera of image orthicon type is mostly used now-a-days. It can be divided in four different sections. These are: (i) the image section, (ii) the electron gun section, (iii) the scanning and deflecting section and (iv) the amplifier section. A diagram of the camera is shown in Fig. 12.4.

The image section is the most vital part of the tube where the image of the scene to be televised is first focussed by an optical lens on a thin glass surface E coated with photo sensitive film. The photo sensitive surface emits photo electrons from different points according to the light intensity of the image. The electrons emitted from the right hand side of E are attracted towards the screen S kept at a positive potential and are made to pass through its meshes. The number of meshes of the screen is about 1,000 per inch and is fixed at the left hand side of the glass target T of low resistivity at a distance of few thousandths of an inch. The electrons are focussed on the target T by the help of the electrostatic field produced by the grid G_6 and the axial magnetic field of the focussing coil. Secondary electrons are now emitted from the different points of T which are attracted to S leaving positive charges at different points in proportion to the light intensity of the image.

The electron gun consists of a cathode K to emit electrons in the form of a narrow beam which is focussed on the target by using a number of cylindrical grids. In the figure, G_1 is the control grid, G_2 is the accelerating grid and G_4 is the focussing grid. The control grid G_1 is utilized for controlling the number of electrons in the beam which can be aligned by the help of the alignment coil.

The electron beam during its movement through the scanning section is deflected by horizontal and vertical deflecting coils and is kept narrow by the help of the focussing coil placed outside the scanning section. A decelerator grid G_5 is kept close to the target so that the electrons in the beam strike the target with a slow velocity. A part of the electrons when strike the target neutralize positive charges developed at different portions on it while the remaining electrons are turned back in the return beam. As a result electrons in the return beam vary in accordance with the intensity of the image and it is therefore current modulated.

The return beam strikes the grid G_2 which helps to emit secondary electrons. The emitted electrons are then deflected in to the multiplier section by the deflecting grid G_3. The multiplier has a number of surfaces for emitting higher and higher secondary electrons. The amplified stream of secondary electrons so produced is finally passed through the load resistor R_L across which the output is taken through a capacitor C. The maximum output current thus obtained represents the black portion of the scene while the less current corresponds to lighter shades.

Vidican: The television camera of vidicon type is simpler than the other cameras and its cost is also lower. But the camera provides less fineness of resolution and so is used mainly for televising movie film. A diagram of the camera is shown in Fig. 12.5.

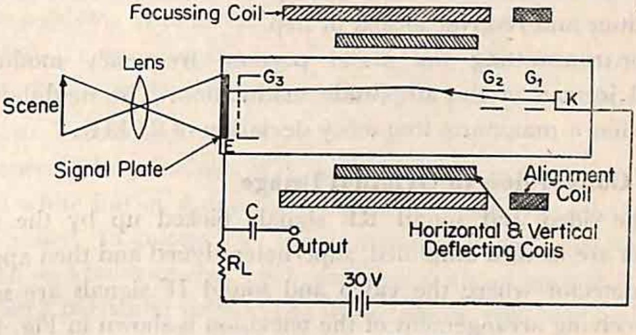


Fig. 12.5

The image section of this camera consists of a thin conducting metallic signal plate which is transparent to light. As before, the image of the scene to be televised is focussed by an optical lens on one side of the signal plate while the scanning is done by a narrow electron beam on the other side of the plate coated with a film of photo-conducting substance. When the image of the scene is focussed on the photo sensitive surface, its different parts get different resistance values according to the light intensity of the image.

The electron gun consists of a cathode K to emit electrons, a control grid G_1, an accelerating grid G_2 and an anode grid G_3. The anode grid is placed in front of the photo-conducting surface so that the electrons of the beam can easily pass through its meshes on the surface. Here also the alignment coils are used for aligning the electron beam, focussing coils make the beam narrow and the horizontal and vertical deflecting coils serve the purpose of deflection.

One major disadvantage of this camera is that the resistance of the photo-conductive film does not change instantaneously with the variation of the intensity of light.

12.2.2 Transmission of Signals

In TV, the picture signal is transmitted by modulating a RF carrier wave in amplitude. The carrier has a frequency range of

54-216 or 470-890 MHz, in general. In practice, a few other signals called synchronizing signals are properly added with the picture signal for obtaining the so-called video signal of bandwidth 4.5 kHz. The function of the synchronizing signal is to maintain correct timing of the horizontal and vertical sweep motion and also to keep the transmitter and receiver locked in step.

For transmitting the audio portion, frequency modulation is applied instead of the amplitude modulation. The modulated sound carrier has a maximum frequency deviation of 25 kHz.

12.2.3 Conversion to Original Image

The video and sound RF signals picked up by the receiving antenna are in turn amplified, superheterodyned and then applied to a video detector where the video and sound IF signals are separated. The receiving arrangement of the television is shown in Fig. 12.6.

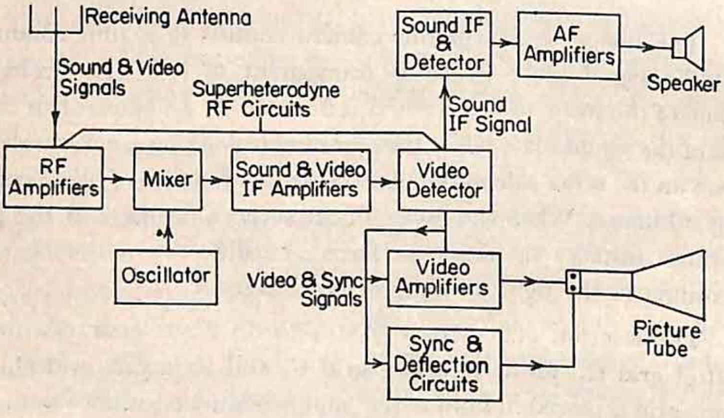


Fig. 12.6

The sound IF signal is applied to the separate portion of a receiver which after audio amplification goes to a loudspeaker. The video signal, on the other hand, is amplified by a video amplifier and then reassembled by an electronic beam on the picture tube or kinescope which is basically a specially equipped cathode ray tube. The kinescope has a fluorescent screen instead of the mosaic plate so that when electrons strike it with high energy luminous radiation comes out. On the fluorescent screen, therefore, the brightness of the electron beam is varied with the variation of the amplitude of the picture signal and so with the brightness of the transmitted image.

12.3 High Voltage Power Supply

To the anode of the picture tube of a television set, voltage of the order of 5,000 to 10,000 volts is applied from a high voltage power supply. A high voltage of this order is essential for producing an intense electron beam over the screen of the picture tube. In addition to this high voltage power supply there is also a conventional rectifier power supply for applying voltages to the electrodes of the tubes and to the electron gun. These voltages are, of course, low and so named as low voltage power supply to distinguish it from the high voltage one.

12.4 Colour Television

In general, the principles of colour television are similar to that of black and white but in actual cases the designs and constructions are too complicated. In colour TV, the illuminated image is televised by using three separate cameras, each provided with an optical filter for transmitting a particular colour. The three colours, red, blue and green are used in practice as others can be obtained by their proper combination.

The tricolour picture tube has three electron guns, one for each of the colour. The screen of the tube is made by a series of three dots of phosphor sensitive for the three colours, instead of a continuous layer. Between the electron guns and the screen a shadow mask is placed whose number of holes is equal to the number of group of dots. The guns are oriented in such a manner that their beams pass at slightly different angles through the same aperture of the mask at a time. These three are then incident simultaneously on red, green and blue dots on the screen accordingly as they are originated in the electron beams. This arrangement is shown in a simplified form in Fig. 12.7.

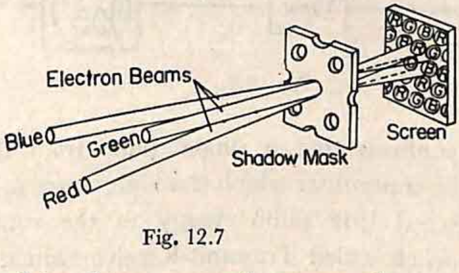


Fig. 12.7

If the distance of the picture screen is greater, the three dots cannot be differentiated individually rather it appears as a composition of three colours.

RADAR

12.5 Introduction

The term 'Radar' is the abbreviation of 'Radio Detection And Ranging'. As the name implies, it detects objects and determine their direction and distance. Radar has wide applications in various fields. It was used originally during the second world war for early warning of approaching enemy planes. But soon the war time applications were extended to different fields like mapping of thunderstorms and other meteorological disturbances, studying the characteristics of moon, navigational helps, etc. Fire control radars, later developed, are now used in most military airplanes.

12.6 Operation of Radar System

A simplified block diagram of a Radar unit is shown in Fig. 12.8. It consists essentially (i) *a powerful transmitter*, (ii) *a directional antenna*, (iii) *a sensitive receiver* and (iv) *a suitable indicator*.

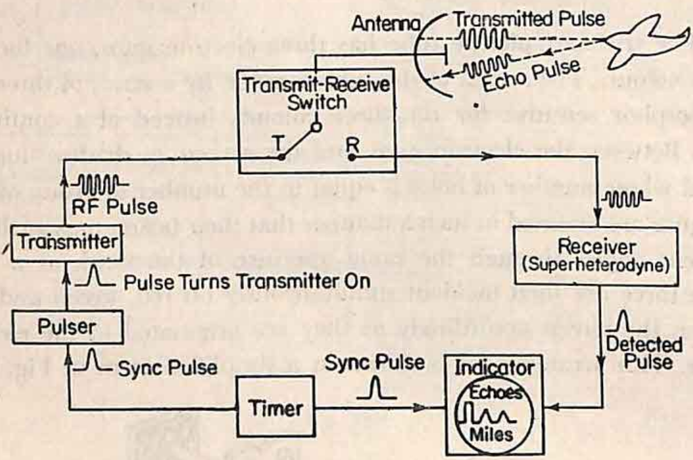


Fig. 12.8

The timer confirms that a single pulse from the modulator (pulser) goes to the transmitter which is a high power magnetron. The transmitter sends out VHF radio energy to the rotating antenna through a T–R switch called Transmit-Receive switch. The antenna sends out the radio energy into space wherefrom a weak echo may come back to the same antenna in case when the transmitted pulse hits an object. If the transmitted beam is reflected back from the centre of the object, the echo signal becomes maximum. In actual case, this is done suitably by rotating the antenna used. The transmitted pulse is recorded visually from the indicator scale.

The 'fast-acting' T–R switch has automatically come to the 'Receive' position by this time. The reflected weak pulse obtained by the T–R switch is amplified and detected from its RF carrier by using superheterodyne circuit. The amplified signal is then presented to the cathode ray indicator tube to disclose the intelligence it contains.

If D be the distance of the object and c the velocity of the waves then the time t required for the waves to return back to the base from an electrically conducting object is given by,

$$t=\frac{2D}{c} \qquad \ldots \qquad (12.1)$$

The distance between the original and echo pulse can be read off directly in km giving the 'range' of the object while the direction of the antenna gives the 'azimuth' of it.

Several methods can be applied for displaying the azimuth on the indicator. Out of which the plan position indicator, abbreviated as PPI, is considered to be the most useful one.

Self-Test

Read each of the following and provide the appropriate words:

(a) In practice, all the electrical impulses of the different picture elements are picked up one after another and then transmitted rapidly through a single channel which is called TV —.

(b) The method of linear — scanning is used widely now-a-days.

(c) The entire picture is scanned about — times per second depending on the frequency of the power supply.

(d) The modulated sound carrier has a maximum frequency deviation of — kHz.

(e) In a colour TV the three colours —, — and — are used as others can be obtained by their proper combination.

(f) The term 'Radar' is the abbreviation of — — and —.

(g) The distance between the original and echo pulse can be read off directly in km giving the — of the object while the direction of the antenna gives the — of it.

Review Questions

1. With a suitable diagram explain briefly the plan of a television system.

2. What is meant by TV scanning? Clearly explain the method of linear interlaced scanning. Indicate how signals are transmitted in a TV.

3. Discuss briefly about the receiving arrangement of a TV system. Give a block diagram.

4. Write a note on colour television.

5. Briefly discuss the operation of a Radar system.

CHAPTER 13

SEMICONDUCTORS

13.1 Introduction

Semiconductor is a solid whose resistivity lies between conductor and insulator. A conductor and an insulator are first distinguished by their extreme values of electrical conductivity. A conductor has a conductivity of 10^4 to 10^6 ohm^{-1} cm^{-1} while the conductivity of an insulator is less than 10^{-6} ohm^{-1} cm^{-1}. Moreover, the conductivity of a conductor decreases with the increase of its temperature whereas that for an insulator increases slightly with increasing temperature. In addition to conductors and insulators, there is a class of solids with intermediate values of electrical conductivity in the range 10^{-6} to 10^3 ohm^{-1} cm^{-1} and whose conductivity increases more strongly with increasing temperature. Such solids are called semiconductors.

Transistors, metallic rectifiers, integrated circuits, junction diodes, zener diodes, tunnel diodes, etc. are examples of semiconductors. They are used widely in radio and TV receivers, in computers and in various electronic instruments. The controlling function of a vacuum tube is similar to that of a semiconductor but it is rapidly replacing vacuum tubes because of added advantages. Some of which are:

(i) Semiconductor is solid. Therefore there is a little chance of vibration as in vacuum tube.

(ii) Little power is required for a semiconductor and also it radiates less heat than in a tube.

(iii) They do not need time for warm up and so operate immediately with the application of power.

(iv) A semiconductor does not undergo any chemical deterioration which occurs in a tube cathode.

(v) A semiconductor is small in size and light in weight.

13.2 Current Carriers

In vacuum tubes, negatively charged electrons are considered as the current 'carriers'. In order to explain current flow in semiconductor diodes and transistors this concept must be modified by the addition of positive charge carriers known as 'holes', which have mass, mobility and velocity. Current flow in semiconductors is thus carried on by the flow of both negative charges (free electrons) and positive charges (holes). Holes are usually attracted by free electrons and when they combine, the free electron 'fills' the hole neutralizing its charge. When this happens the hole and free electron both are lost as current carriers and form new current carrier at other points in the semiconductor.

Impurity like arsenic or antimony (pentavalent atoms) increases the conductivity of silicon, which has four valence electrons in its outer shell, by increasing the number of negative charge carriers. Silicon which has been doped here with arsenic or antimony is designated as '*N*-type'. Similarly impurity like indium or gallium (trivalent atoms) increases the conductivity of silicon by increasing the number of positive charge carriers. For this reason, silicon which has been doped with indium or gallium is called '*P*-type'. Current flow in *N*-type and *P*-type silicon is carried on by 'free electrons' and 'holes' respectively and these are known as majority carriers. Some holes, however, exist in *N*-type silicon and some free electrons in *P*-type. But these are in the minority and are therefore called minority carriers.

By applying an external battery voltage V_{AA} across the semiconductor, as shown in Fig 13.1, one can easily control the movement

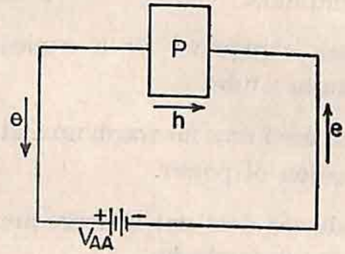


Fig. 13.1

of current carriers. In the *P*-type silicon holes are repelled by the positive terminal of the battery and move toward the negative terminal. While free electrons from the negative terminal move toward the hole. Thus a combination of the two takes place continuously and the flow of current is maintained in the external circuit.

13.3 Operation of Junction Diode

When *P*-type and *N*-type silicon are joined together a junction diode is formed. The diode thus created (Fig. 13.2) has a characteristic to pass current in one direction readily but not in the other. This unique characteristic may be explained by considering the theory of negative and positive carriers.

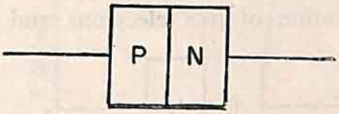


Fig. 13.2

In Fig. 13.3, the *P-N* junction has been connected with the battery V_{AA} as shown. Free electrons from the negative terminal of V_{AA} enter the *N*-type silicon and repel the free electrons therein. Similarly, the holes in the *P*-type silicon are repelled by the positive battery terminal and thereby move toward the *P-N* junction where a combination of free electrons and holes takes place. Although there is usually a potential barrier in the diode that prevents electrons and holes to combine, under the influence of the electric field of the battery the holes move to the right and the electrons to the left. At such times a covalent bond near the positive terminal of the battery breaks down causing an electron to liberate and enter the positive terminal. As a consequence, a new hole is further created which moves to the right toward the *P-N* junction. The process is a continuous one and so a current flow is maintained in the circuit. If the value of V_{AA} is increased, the current flow in the diode also increases. A diode connected in such a fashion with positive battery terminal to the *P*-type and negative battery

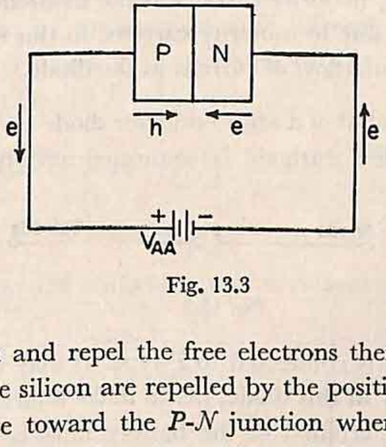


Fig. 13.3

terminal to the *N*-type is called 'forward bias' and the diode is said to have a low forward resistance.

If the polarities of the battery V_{AA} are reversed, as shown in Fig. 13.4, no combination of free electrons and holes takes place.

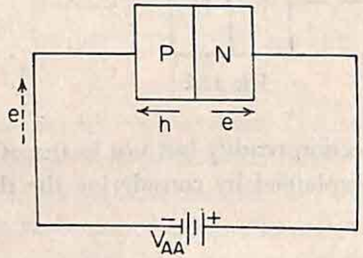


Fig. 13.4

As a matter of fact, majority carriers in the diode do not support any current flow. Only due to minority carriers, in this reverse-bias condition, there is a minute flow of current in the diode.

The circuit symbol of a semiconductor diode is shown in Fig. 13.5. The terminal marked cathode is connected to *N*-type material while that marked anode is connected to *P*-type. It may be noted therefore that to flow current in this diode, i.e. to make a forward-bias arrangement the negative terminal of the battery must be connected to the cathode and the positive to the anode.

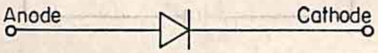


Fig. 13.5

13.3.1 Characteristic Curve

The characteristic curve of a diode shows how current varies with the voltage applied across it. This is experimentally obtained by varying the voltage in steps and noting the corresponding current. A graph is then drawn by plotting current versus voltage as shown in Fig. 13.6. It is to be noted from the figure that when the voltage applied is low, very little current flows in the diode but after a certain level is reached, slight increase of the applied voltage causes a large increase of current in the diode.

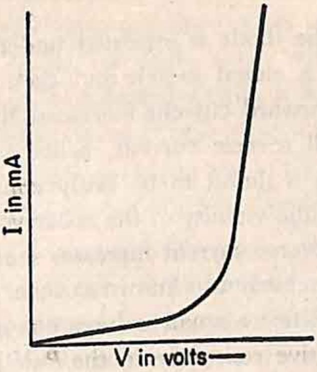


Fig. 13.6

13.4 Zener Diode

We have seen that a junction diode is operated suitably by using forward-bias arrangement. In zener diode, its unique reverse-bias characteristic provides some important different applications from those of the crystal diode. A zener diode can be represented symbolically as shown in Fig. 13.7.

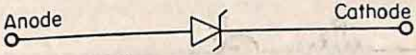


Fig. 13.7

Fig. 13.8 shows the nature of current-voltage characteristic of the

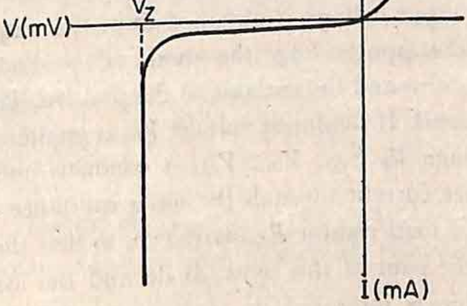


Fig. 13.8

zener diode. When the diode is operated under forward-bias condition, it behaves like a closed switch and then with an increase in applied voltage the forward current increases. But when the diode is reverse-biased a small reverse current, called saturation current I_s, begins to flow which is found to be fairly constant until the zener breakdown region, in the vicinity of the zener voltage V_z is attained. In this vicinity the reverse current increases sharply to a high value. This sudden increase in current is known as zener current or avalanche effect. In this region since a small voltage change alters the current considerably the effective resistance in the *P-N* junction also changes dramatically.

Manufacturers supply a specification sheet for each type of zener diode. The breakdown voltage in a diode mainly depends on the material used in its construction.

13.4.1 Applications

Zener diode is used conveniently as a regulator in power supply. A zener regulator circuit for explanation is shown in Fig. 13.9 In the

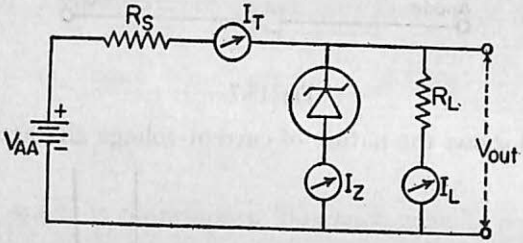


Fig. 13.9

circuit the input is a d.c. voltage whose voltage variations are to be regulated. The input voltage is obtained from the output of a power supply. Across the input voltage the anode of the diode is connected to the negative point and the cathode to the positive. That is the zener is reverse-connected. If the input voltage V_{in} is greater than the zener breakdown voltage V_z (i.e., $V_{in} > V_z$), it conducts and draws a relatively large zener current through the series resistance R_s. Across the output there is a load resistor R_L, as shown, so that the total current through R_s is the sum of the zener diode and the load currents. If the input voltage is increased the current through both the zener diode and the load will also increase. The zener diode resistance, however, decreases simultaneously causing an increase of the voltage drop across R_S. As a result, across the zener regulator a substantially constant output voltage is obtained within a fraction of a volt even when the input voltage is varied over a range of several volts.

In order to analyse the circuit to Fig 13.9 which contains linear (resistors) and nonlinear (zener diode) elements apply Ohm's and Kirchhoff's laws.

Let us consider the operation of the circuit when the voltage source V_{AA} is constant but the load current I_L varies. Let a constant output voltage V_{out} is required across the load. The two currents, $I_z = V_{out}/R_z$ (R_z=zener resistance) and $I_L = V_{out}/R_L$ combine to form the total current I_T. Thus we can write,

$$I_T = I_z + I_L \qquad \ldots \qquad (13.1)$$

The voltage across R_s is equal to the product of I_T and R_s.

i,e., $$V_{R_s} = I_T \times R_s \qquad \ldots \qquad (13.2)$$

But, $$V_{AA} = V_{R_s} + V_{out} \qquad \ldots \qquad (13.3)$$

So if V_{AA} remains constant and it is necessary that V_{out} remains constant then V_{R_s} must also remains constant. Therefore the total current flowing in the circuit I_T must remain fixed despite variations in load current. This is accomplished only by compensating changes in I_z where,

$$I_z = I_T - I_L \qquad \ldots \qquad (13.4)$$

supposing I_T is a constant and I_L can vary.

If the regulator circuit is properly designed, the increased voltage across R_s, ΔV_{R_s}, should be approximately equal to the increased supply voltage ΔV_{AA} and V_{out} would drop back to its original value. Similarly, a decrease in V_{AA}, would result in a decrease in I_z and hence in I_T.

In addition to the regulator diode described above, there are also voltage reference diodes whose zener voltage is so stable that it can be used as a laboratory standard or as a reference voltage.

13.5 Tunnel Diode

We know that the characteristics of a solid-state diode depend on the semiconductor material from which the diode is manufactured and also on the nature and extent of doping of this material. A tunnel diode is a *P-N* junction device with a high concentration of impurities in its semiconductor elements. Due to the large number of impurities, the space charge region at the junction is very thin and as a result electrical charges move easily through it. This process is called 'tunnelling'. The symbol of a tunnel diode is shown in Fig. 13.10.

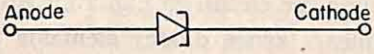


Fig. 13.10

A tunnel diode conducts well for both forward and reverse-biased. However, the importance of the diode stems from the uniqueness of its forward voltampere characteristics. Fig. 13.11 shows a typical characteristic curve of the diode. As the forward bias is increased from zero to the value V_M, current increases to a value I_M. With further increase of forward bias from V_M to V_V, current decreases from I_M to I_V (valley current). As forward bias increases beyond V_V, current begins to rise again. The area of the voltampere characteristic between V_M and V_V is known as the negative resistance region of the diode because of unique decrease of the diode current. It is interesting to note that as the forward voltage across the diode increases to V_{FM}, the normal diode current occupies the same level as the tunnel current previously reached at V_M. The voltage V_{FM} is sometimes termed as the 'forward voltage' of the diode. The unique portion from V_M to V_V of the tunnel diode's characteristics is of particular importance to circuit designers.

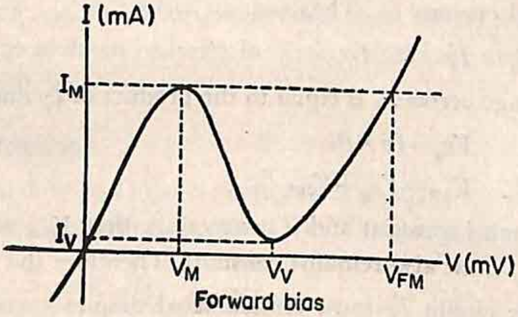


Fig. 13.11

A tunnel diode has applications as an amplifier, oscillator, or switching element. These are, in fact, the advantages over a conventional diode which cannot act for such purposes.

Self-Test

Read each of the following and provide the appropriate words:

(a) The electrical conductivity of semiconductors are in the range of — to — $\text{ohm}^{-1}\ \text{cm}^{-1}$.

(b) Germanium and silicon in their pure form are —. (conductors/insulators)

(c) Silicon when doped with indium forms — semiconductor.

(d) To forward bias a junction diode the — terminal of a battery is connected to *P*-type diode and the — terminal to the *N*-type diode.

(e) The forward resistance of a silicon diode is — and the reverse resistance is —.

(f) When used as a voltage regulator a zener diode must be — biased.

(g) A tunnel diode is a *P-N* junction device with a high concentration of impurities in its semiconductor elements. (True/False)

(h) A tunnel diode will not pass current when it is reverse biased. (True/False)

Review Questions

1. What are the advantages of a semiconductor over a vacuum tube?

2. How can a semiconductor be identified from a conductor and an insulator?

3. What is meant by current carriers? Explain how *P*- and *N*-type semiconductors are formed.

4. Describe with a circuit diagram the operation of a junction diode.

5. What do you mean by 'forward-bias' and 'reverse-bias' arrangements?

6. Explain with necessary diagrams the characteristic curves of a junction diode, zener diode and a tunnel diode.

7. Briefly describe the applications of a zener diode and a tunnel diode.

CHAPTER 14

TRANSISTORS

14.1 Introduction

Scientific interest in semiconductor devices led to the discovery of the transistor. In 1948 Bardeen and Brattain while working at the Bell Telephone Laboratories announced the development of the first transistor. One of the great advantages of a transistor over a vacuum tube is that it is small in size and it does not require any filament power. The supply voltage of a transistor is also very low and it operates as soon as power is applied. In addition, the circuit connection of a transistor is very simple than that of a tube.

14.2 Classification

Transistors are of many types which may be broadly classified as follows:

(i) *Depending on the basic materials from which they are formed.* In this category we have silicon and germanium transistors. Now-a-days most transistors are of silicon type.

(ii) *Depending on the number of elements used.* Here we have triode or three-element transistor and the tetrode or four-element transistor.

(iii) *Depending on the ability to dissipate power.* Here we have a wide range from low power (below 50 mW) to high power (2 W and above) type.

(iv) *Depending on the process of construction.* In this category we have various junction transistors such as grown junction, alloy junction, mesa, epitaxial mesa, planar transistors, drift-field and point-contact transistors.

Transistors are of different in sizes and shapes. There are variations also in the manner of mounting and in the basing arrangements. Some transistors are socket mounted while others have flexible leads for directly soldering in a circuit.

14.3 Junction Transistor

The junction transistor, a radically new type of transistor, was first developed by Shockley in 1949 just a year later of the discovery of the point contact transistor. A junction transistor, now widely used, is nothing but a combination of two P-N junctions. A typical junction transistor formed by sandwiching a thin *N*-type layer between two *P*-type layers is illustrated in Fig. 14.1. Such a transistor is called a *P-N-P* junction transistor or in short a *P-N-P* transistor. If, alternately, there are two *N*-type layers on either side of a *P*-type layer it is called *N-P-N* transistor.

Of the two *P-N* junctions one is forward biased while the other is reverse biased, i.e. the *P*-layer is connected respectively with the positive and negative terminals. There are three leads from individual metallic plates which make contact with the respective crystals. Referring to Fig. 14.1. The *N*-layer in the middle is called the 'base', the forward biased *P*-layer on the left is the 'emitter' while the reverse biased *P*-layer on the right is the 'collector'.

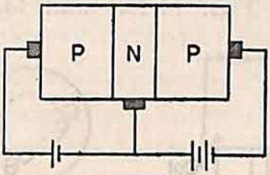


Fig. 14.1

14.4 Transistor Symbols

Internationally used symbols for *P-N-P* and *N-P-N* transistors are shown in Figs. 14.2(a) and 14.2(b) respectively. These symbols are required for representing transistors in electronic circuits. In the figure, the element with the arrow head is the emitter and its symmetrical counterpart is the collector. Of the three leads, the third one is called base. In a *P-N-P* transistor the emitter arrow points to the base while in the *N-P-N* type the arrow points away from the base. The significance of the arrow is that it indicates the direction of emitter current flow, i.e. opposite to the direction of electron flow, under forward biased conditions.

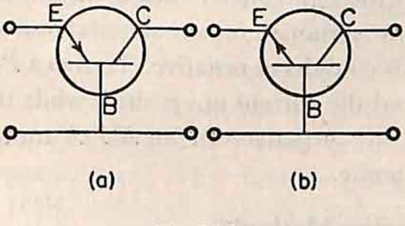


Fig. 14.2

The emitter, base and collector leads of a transistor can be conveniently identified by the following two ways:

(i) The central lead corresponds to the base. The spacing between the emitter lead and the base lead is less than the spacing between the base lead and the collector lead.

(ii) If the leads are along the circumference of a circle then the centre one is called base. The emitter and the collector leads are then identified by reading clockwise from the base. In such reading first comes the collector and then the emitter.

The above two methods of identification of transistor leads are shown symbolically in Figs. 14.2(c) and 14.2(d) respectively. The collector lead can also be identified by a dot which is pointed on the body of the transistor close to the collector.

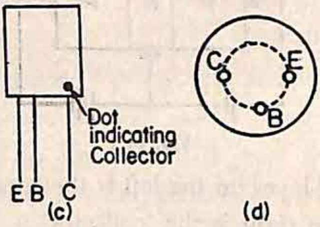


Fig. 14.2

According to the sign conventions, a current flowing into a transistor through any terminal is considered positive while a current coming out of it is considered negative. Thus in a *P-N-P* transistor, the emitter voltage and the current are positive while the collector voltage and the current are negative. In an *N-P-N* transistor the signs are obviously just opposite.

14.5 Manufacturing Methods

For the manufacture of transistors both germanium and silicon are found to be suitable. However, the germanium is limited to a temperature of about 85°C while silicon is capable of operating to 200°C. Several methods are employed for the manufacture of junction transistors, depending mainly on the fabrication processes of the *P-N* junction. Two such methods are briefly discussed below.

(a) *Alloy or fusion method*—In this method for producing a *P-N-P* transistor two small pellets of indium of slightly different diameters are placed on either side of a wafer of *N*-type germanium, say, with the help of a suitable jig. This assembly is heated for a few minutes at a temperature of about 600°C as a result of which indium melts and combines with the germanium. After taking out from the furnace three wires are soldered for the emitter, base and the collector leads. The larger *P*-layer forms the collector while the smaller one is the emitter of a transistor.

An *N-P-N* transistor can also be made by a similar process using *P*-type germanium wafer and taking arsenic or antimony in place of indium.

Since here the *P-N* junction is produced by alloying or fusion the transistors so formed are known as alloyed or fused junction transistors.

(b) *Grown junction method*—The grown *P-N-P* junction is made by adding appropriate acceptor and donar impurities alternately to a molten bath of a semiconductor material. The growth process is repeated at a regular interval of time and pulling the crystal simultaneously. The crystal is then cut into pieces parallel to the junction and this is subsequently diced. Transistors so produced are called grown junction transistors.

14.6 Circuit Configurations

As discussed earlier, a transistor has three internal electrodes known as emitter, base and collector. If it is to be used to study as a four-terminal device, two for the input and two for the output, then one electrode must be kept common. Accordingly there are three possible circuit arrangements. These are: (i) the common emitter, (ii) the common base and (iii) the common collector circuits. Instead of the term 'common', sometimes the word 'grounded' is also used, such as grounded emitter, etc. The three circuit configurations are illustrated in Figs. 14.3(a), (b) and (c) respectively. When a transistor

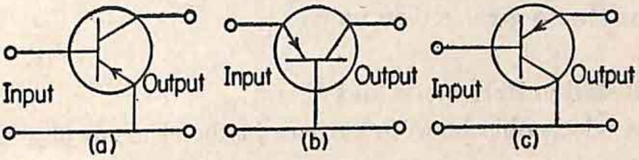


Fig. 14.3

is used in common emitter configuration, the input signal is applied between base and emitter while the output is obtained from the collector to emitter. The emitter in such a case is thus common to both the input and the output circuits and hence the name common emitter. Similarly in a common base or in a common collector circuit the base or the collector serves as a common reference for both the input and output signal. The common emitter is, however, most frequently used as it provides suitable voltage, current and power gain in different electronic circuits.

14.7 Current Gain

In a common base circuit the collector current is controlled by the variations of emitter current. This gives one important control characteristic of a transistor designated by α, where α is defined as the ratio of the change in collector current (ΔI_C) to the change in emitter current (ΔI_E) when the collector voltage (V_{CB}) is maintained at a constant value. Mathematically, this can be expressed as,

$$\alpha=\left(\frac{\Delta I_C}{\Delta I_E}\right)_{V_{CB}=\text{constant}} \quad \ldots \quad (14.1)$$

α is also sometimes designated by the letters h_{fb} and is called the forward-current-transfer ratio. In a common-base arrangement, since the collector current is slightly less than the emitter current, α will be slightly less than unity.

In a common emitter circuit, the input signal is applied to the base. This gives another important control characteristic designated by β, where β is defined as the ratio of the change in collector current (ΔI_C) to the change in base current (ΔI_B) when the collector voltage (V_{CE}) is kept constant. Mathematically, this can be expressed as,

$$\beta=\left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}=\text{constant}} \quad \ldots \quad (14.2)$$

β is also sometimes designated by the letters h_{fe} and it is the current amplification factor in a common emitter amplifier. Since small changes in base current produce large changes in collector current, the value of β will be always greater than unity.

14.7.1 Relation Between α and β

The relationship between currents in the elements of a transistor is expressed as,

$$I_E=I_B+I_C \quad \ldots \quad (14.3)$$

Now we know that for a small change in emitter current ΔI_E, there is a corresponding change in base current ΔI_B and in collector current ΔI_C. Thus,

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\text{or,} \quad \Delta I_B = \Delta I_E - \Delta I_C \qquad \ldots \qquad (14.4)$$

Therefore,

$$\frac{\Delta I_C}{\Delta I_B} = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$$

$$= \frac{\Delta I_C / \Delta I_E}{1 - \dfrac{\Delta I_C}{\Delta I_E}} \qquad \ldots \qquad (14.5)$$

As defined, when V_{CB} is constant the ratio $\Delta I_C / \Delta I_E$ equals α and when V_{CE} is constant the ratio $\Delta I_C / \Delta I_B$ equals β. So for constant V_{CB} and constant V_{CE} we may write equation (14.5) as,

$$\beta = \frac{\alpha}{1-\alpha} \qquad \ldots \qquad (14.6)$$

$$\text{or,} \quad \alpha = \frac{\beta}{1+\beta} \qquad \ldots \qquad (14.7)$$

It is clear that as α approaches towards unity, β becomes increasingly larger. For a transistor whose α is 0.98, β becomes 49 while an α of 0.99 gives β of 99. So during experiment α must be measured very accurately to avoid formula error in β.

14.8 Static Characteristics with Common Base Configuration

The performance of transistors are determined by studying the characteristic curves of their voltage and current relations just as for electron valves. The circuit diagram for studying the characteristcs under common base configurations of a *P-N-P* junction transistor is shown in Fig. 14.4.

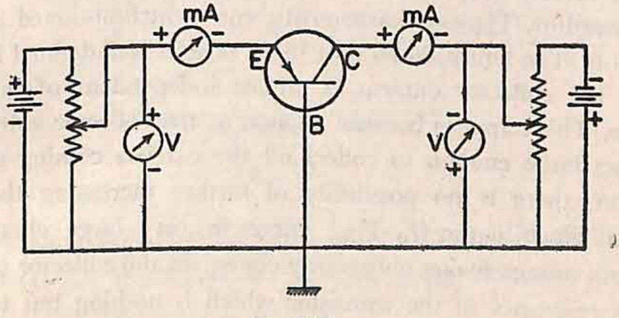


Fig. 14.4

(a) Input Characteristics—The curve obtained by plotting emitter current (I_E) against the emitter voltage (V_{EB}) keeping the collector voltage (V_{CB}) as parameter is called the input characteristic of a transistor. Typical input characteristic of a transistor is shown in Fig. 14.5. The figure shows that the emitter current increases exponentially with the emitter voltage and that a very small change in emitter voltage produces a large flow of emitter current. Different curves may be similarly drawn by plotting I_E against V_{EB} with a constant collector voltage V_{CB} for each curve.

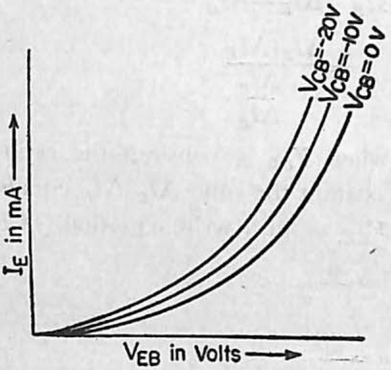


Fig. 14.5

The slope of the curve for a fixed collector voltage is then considered to get the input resistance at the point. On the input characteristic of a transistor the collector voltage has very little influence.

(b) Output Characteristics—The curve obtained on plotting collector current (I_C) against the collector voltage (V_{CB}) keeping the emitter current (I_E) as parameter is called the output characteristics of a transistor. Typical characteristic curves such obtained is shown in Fig. 14.6. The figure shows that there exists a well-defined knee above which the collector current is almost independent of the collector voltage. This happens because as soon as the collector voltage (V_{CB}) becomes large enough to collect all the carriers coming to the *C–B* junction, there is no possibility of further increasing the collector current. Since in the (I_C–V_{CB}) curves a very large change in the collector voltage makes only a tiny change in the collector current, the output resistance of the transistor which is nothing but the ratio of voltage to current change becomes very high.

It is to be noted here that even for zero collector voltage we may draw the output characteristic of a transistor as then also the collector

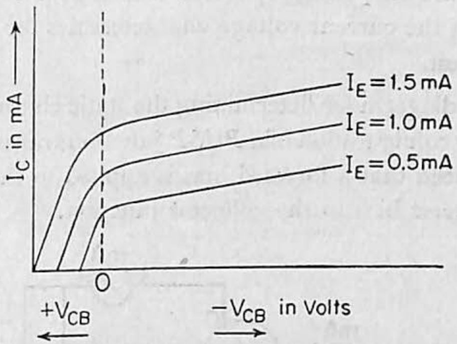


Fig. 14.6

currents are present corresponding to different emitter currents. As the emitter and collector regions in a transistor are very close to each other, holes injected at the emitter are received by the collector even for a zero collector voltage.

(c) Transfer Characteristics—The curve obtained on plotting collector current (I_C) against the emitter current (I_E) keeping the collector voltage (V_{CB}) constant is called the transfer characteristic of a transistor. Typical transfer characteristic of a transistor is shown in Fig. 14.7. The figure shows that the characteristic is almost linear.

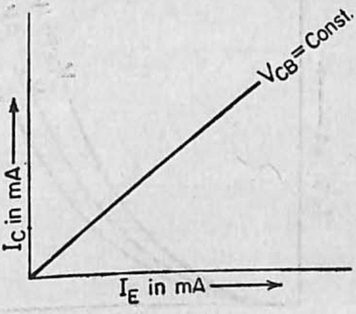


Fig. 14.7

It is seen experimentally that the value of I_C is always slightly less than the value of I_E. The slope obtained by considering the curve obviously provides the current amplification factor (α).

14.9 Static Characteristics with Common Emitter Configuration

Transistors are frequently operated under common emitter configuration and so the current voltage characteristics for this configuration are of interest.

The circuit diagram for determining the static characteristics under common emitter configuration of a *P-N-P* junction transistor is shown in Fig 14.8. It is seen that a forward bias is applied to the emitter junction while a reverse bias to the collector junction.

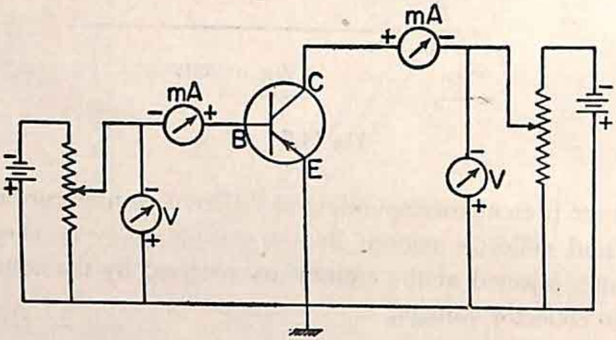


Fig. 14.8

(a) Input Characteristics—Values of base current (I_B) is plotted against base to emitter voltage (V_{BE}) for a fixed V_{CE}. The nature of the curves obtained for different sets of V_{CE} is shown in Fig. 14.9.

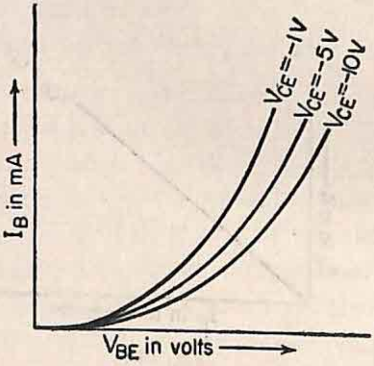


Fig. 14.9

(b) Output Characteristics—Values of collector current (I_C) is plotted against collector to emitter voltage (V_{CE}) for a fixed I_B. The nature of the curves obtained for different sets of I_B is shown in Fig. 14.10. It is seen that the slope obtained for the present case is much

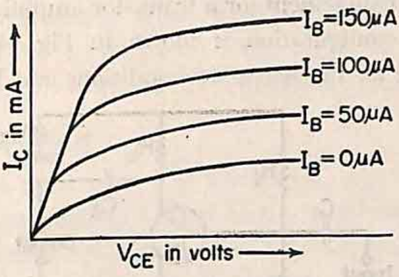


Fig. 14.10

higher than that we get by considering Fig. 14.6, suggesting that the output resistance of a transistor is less, i.e., the current gain is greater for common emitter configuration than that for common base.

(c) Transfer Characteristics—Values of collector current (I_C) is plotted against the base current (I_B). The characteristic is shown in Fig. 14.11.

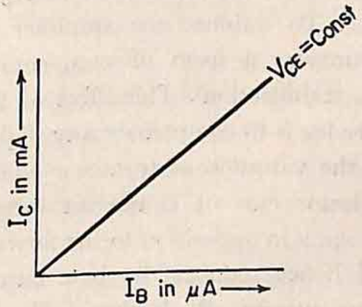


Fig. 14.11

14.10 Biasing Methods

By the term biasing of a transistor we mean application of an appropriate current to its base terminal. This is similar to the application of a voltage to the grid terminal of a valve. The following is the main features of a good biasing system.

(i) The bias related to the emitter base and the collector base junctions should be provided by one battery.

(ii) The gain of the transistor should not be influenced by negative feedback.

(iii) The desired operating point must be stable irrespective of change in temperature.

The biasing arrangement for a transistor amplifier operated under common emitter configuration is shown in Fig. 14.12. The biasing circuit agrees well all the necessary conditions and hence it is almost universally used. In the figure a common power supply V_{CC} has been used so that both the base and the collector terminals receive a d.c. negative voltage with respect to the emitter. Resistors R_1 and R_2 constitute a voltage divider on the base while R_L serves the purpose of a load resistance. To stabilize the amplifier and to protect the transistor against runaway a form of compensation is required to use, known as 'bias stabilization'. The effect of the resistor R_E connected to the emitter leg is to compensate any slight increase in collector current due to the variation of transistor characteristics. In fact, an increase in collector current causes an increased voltage drop across R_E. This voltage is in opposition to the forward bias in the base-emitter circuit and hence reduces the base current which in turn reduces the collector current. R_E is thus utilized for balancing the tendency of the collector current to increase in value by providing negative d.c. feedback. In a circuit the values of R_E and R_L are chosen simply by considering the supply voltage and the required operating point.

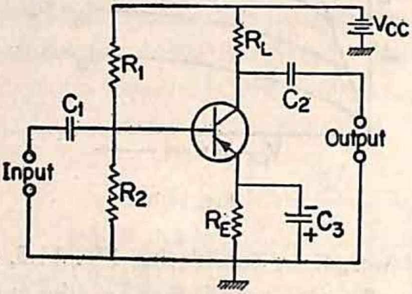


Fig. 14.12

There are three capacitors C_1, C_2 and C_3 in the circuit. The function of C_1 is to couple the input signal to the amplifier while C_2 is used to couple the amplifier output to the next amplifying stage. Of interest is the third capacitor C_3 which is connected in parallel with the emitter resistor R_E. If an a.c. signal is applied to the base of the transistor and the capacitor C_3 is connected across R_E then it provides another path for the a.c. signal current. If the capacitive reactance of C_3 becomes sufficiently low then it acts as a low impedance path. C_3 thus serves as an effective bypass for a.c. signal. In absence of C_3 the gain of the amplifier is considerably reduced due to negative feedback effect.

14.11 Equivalent Circuit

To analyse the performance of transistors, they are conveniently represented by an equivalent circuit. The three sets of parameters used to analyse transistor circuits are: (a) impedance parameters (Z-parameters), (b) admittance parameters (Y-parameters), and (c) hybrid parameters (h-parameters). Of these the equivalent circuit using h-parameters is considered most useful because of the following advantages:

(i) The h-parameters are the easiest to measure.

(ii) The h-parameters are more independent of each other and other variables like operating point, frequency etc.

(iii) The values of h-parameters nearly correspond to actual values of input and output impedances and current gain for most of the applications.

Although different equivalent circuits exist for a transistor, one may convert the parameters of one circuit to other by using some conversion relations. Here we consider only the equivalent circuit by the use of hybrid parameters.

Let i_1, i_2, v_1 and v_2 denote the total instantaneous values of currents and voltages. Then the functional relationships between them for the case of hybrid parameters are written in the form,

$$v_1 = f_1(i_1, v_2) \qquad \ldots \qquad (14.8)$$

$$i_2 = f_2(i_1, v_2) \qquad \ldots \qquad (14.9)$$

From equations (14.8) and (14.9) we get,

$$dv_1 = \left(\frac{\delta v_1}{\delta i_1}\right) di_1 + \left(\frac{\delta v_1}{\delta v_2}\right) dv_2 \qquad \ldots \qquad (14.10)$$

$$di_2 = \left(\frac{\delta i_2}{\delta i_1}\right) di_1 + \left(\frac{\delta i_2}{\delta v_2}\right) dv_2 \qquad \ldots \qquad (14.11)$$

The variational components di_1, di_2, dv_1 and dv_2 may be denoted by I_1, I_2, V_1 and V_2 respectively, where I_1 and V_1 are the input current and voltage of a four pole transistor treating as a 'black box' and I_2,

V_2 are the corresponding output values as shown in Fig. 14.13. Equations (14.10) and (14.11) can now be written in the form,

$$V_1 = h_{11} I_1 + h_{12} V_2 \quad \dots \quad (14.12)$$

$$I_2 = h_{21} I_1 + h_{22} V_2 \quad \dots \quad (14.13)$$

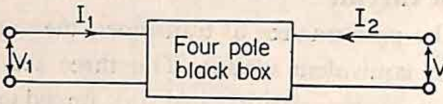


Fig. 14.13

In equations (14.12) and (14.13) the *h*-parameters are defined as,

$$h_{11} = \frac{|V_1|}{|I_1|}\bigg|_{V_2=0} = \text{input impedance with output short circuited,}$$

$$h_{12} = \frac{|V_1|}{|V_2|}\bigg|_{I_1=0} = \text{reverse voltage transfer ratio with input open circuited,}$$

$$h_{21} = \frac{|I_2|}{|I_1|}\bigg|_{V_2=0} = \text{forward current transfer ratio with output short circuited,}$$

$$h_{22} = \frac{|I_2|}{|V_2|}\bigg|_{I_1=0} = \text{output admittance with input open circuited.}$$

It is seen from above that two of the parameters h_{12} and h_{21} are dimensionless while the other two h_{11} and h_{22} have dimensions of impedance and admittance respectively. It may also be noted that out of the four parameters two are measured with output short circuited and two with input open circuited. That is why these are called hybrid or *h*-parameters.

14.11.1 Performance of Transistor Amplifiers

Depending on the mode of operation, transistor amplifiers are divided into three groups. These are (i) common base, (ii) common emitter and (iii) common collector amplifiers. To obtain expressions for various electrical characteristics of a transistor such as impedance, gain, etc. we first consider the case of common base configuration since it gives best illustration of how a transistor works.

The circuit diagram of a common base transistor amplifier is shown in Fig. 14.14(a) while its equivalent circuit using the *h*-parameters is shown in Fig. 14.14(b).

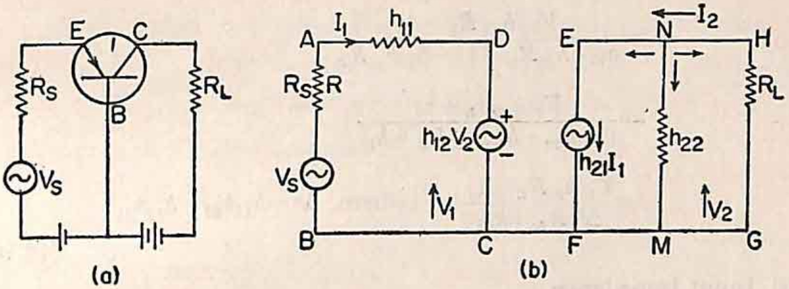


Fig. 14.14

Equating the sum of the voltage drops of the mesh *ABCD*, we have,

$$V_1 = h_{11}I_1 + h_{12}V_2 \qquad \ldots \qquad (14.14)$$

Again, for the output side since the sum of the currents leaving the nodal point *N* are equal to zero, we have,

$$0 = h_{21}I_1 + h_{22}V_2 + \frac{V_2}{R_L} \quad \text{(where, } R_L \text{ is the load resistor)}$$

$$= h_{21}I_1 + \left(h_{22} + \frac{1}{R_L}\right)V_2 \qquad \ldots \qquad (14.15)$$

From equations (14.14) and (14.15) solving for I_1 by the use of determinant we get,

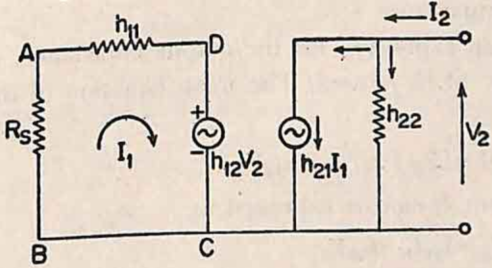


Fig. 14.15

$$I_1 = \frac{\begin{vmatrix} V_1 & h_{12} \\ 0 & h_{22} + \dfrac{1}{R_L} \end{vmatrix}}{\begin{vmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} + \dfrac{1}{R_L} \end{vmatrix}}$$

$$= \frac{V_1\left(h_{22} + \dfrac{1}{R_L}\right)}{h_{11}\left(h_{22} + \dfrac{1}{R_L}\right) - h_{12}\,h_{21}}$$

$$=\frac{V_1\,(h_{22}\,R_L+1)}{h_{11}\,(h_{22}R_L+1)-h_{12}h_{21}R_L}$$

$$=\frac{V_1(h_{22}R_L+1)}{(h_{11}h_{22}-h_{12}h_{21})R_L+h_{11}}$$

$$=\frac{V_1(h_{22}R_L+1)}{\Delta^h\,R_L+h_{11}} \quad \text{(where, } \Delta^h=h_{11}h_{22}-h_{12}h_{21}) \qquad \ldots \quad (14.16)$$

(i) Input Impedance

The input impedance R_{in} is now obtained from equation (14.16) as,

$$R_{in}=\frac{V_1}{I_1}=\frac{\Delta^h\,R_L+h_{11}}{h_{22}R_L+1} \qquad \ldots \quad (14.17)$$

Equation (14.17) shows that,

when $R_L=0$,

$R_{in}=h_{11}$, the short circuit input impedance.

With the increase of R_L, R_{in} also increases as h_{21} is negative in nature and attains a value of $h_{11}-h_{12}\,h_{21}/h_{22}$ for $R_L=\infty$. Thus we see that the input impedance of a transistor varies significantly with the variation of R_L.

(ii) Output Impedance

To get an expression for the output impedance, the equivalent circuit of Fig. 14.15 is used. The mesh equation of the loop *ABCD* is written as,

$$0=(R_S+h_{11})I_1+h_{12}V_2 \qquad \ldots \quad (14.18)$$

and the current I_2 can be expressed as,

$$I_2=h_{21}I_1+h_{22}V_2 \qquad \ldots \quad (14.19)$$

From equations (14.18) and (14.19) solving for V_2 we find,

$$V_2=\frac{\begin{vmatrix} R_S+h_{11} & 0 \\ h_{21} & I_2 \end{vmatrix}}{\begin{vmatrix} R_S+h_{11} & h_{12} \\ h_{21} & h_{22} \end{vmatrix}}$$

$$=\frac{(R_S+h_{11})I_2}{(R_S+h_{11})h_{22}-h_{12}h_{21}}$$

$$=\frac{(R_S+h_{11})I_2}{R_Sh_{22}+\Delta^h} \quad [\because \Delta^h=(h_{11}h_{22}-h_{12}h_{21})]$$

So the output impedance R_{out} is given by,

$$R_{out}=\frac{V_2}{I_2}=\frac{R_S+h_{11}}{R_S h_{22}+\Delta h} \qquad \dots \qquad (14.20)$$

Equation (14.20) shows that,

when $R_S=0$,

$$R_{out}=\frac{h_{11}}{\Delta h}$$

With the increase of R_S, R_{out} also increases and attains a value of $1/h_{22}$ for $R_s=\infty$. Thus R_{out} varies considerably with the variation of R_S.

(iii) Gain

To find the voltage gain of the transistor, let us first calculate the output voltage V_2 by considering equations (14.14) and (14.15). We may write,

$$V_2=\frac{\begin{vmatrix} h_{11} & V_1 \\ h_{21} & 0 \end{vmatrix}}{\begin{vmatrix} h_{11} & h_{12} \\ h_{21} & h_{22}+\frac{1}{R_L} \end{vmatrix}}$$

$$=\frac{-V_1 h_{21}}{h_{11}\left(h_{22}+\frac{1}{R_L}\right)-h_{12}h_{21}}$$

$$=-\frac{V_1 h_{21} R_L}{R_L\Delta h+h_{11}}$$

Therefore, voltage gain $A_v=\frac{V_2}{V_1}=-\frac{h_{21}R_L}{R_L\Delta h+h_{11}}$ $\qquad \dots \qquad$ (14.21)

To get an expression for current gain we just note from Fig. 14.14(b) that,

$$V_2=-I_2R_L$$

and hence substituting in equation (14.15) we have,

$$0=h_{21}I_1-\left(h_{22}+\frac{1}{R_L}\right)R_L I_2$$

$$=h_{21}I_1-(h_{22}R_L+1)I_2$$

or, $(h_{22}R_L+1)I_2=h_{21}I_1$

Therefore, current gain $A_i=\frac{I_2}{I_1}=\frac{h_{21}}{h_{22}R_L+1}$ ... (14.22)

We can now calculate the power gain (A_p) as,

$$A_p=A_v\times A_i$$

Substituting the values of A_v and A_i from equations (14.21) and (14.22) we get,

$$A_p=-\frac{h_{21}R_L}{(R_L\Delta^h+h_{11})}\times\frac{h_{21}}{(1+h_{22}R_L)}$$

$$=-\frac{h_{21}^2\,R_L}{(R_L\Delta^h+h_{11})\,(1+h_{22}R_L)} \quad \text{... (14.23)}$$

The condition for maximum power gain can be obtained by differentiating the expression for A_p with respect to R_L and then equating it to zero.

14.11.2 Relation between the three Modes of Operation

The electrical parameters for both the common emitter and the common collector modes can be found by using the same expressions as obtained for the common base. In general, the transistor manufacturers specify the hybrid parameters only in the common base mode of operation (usually designated in terms of h_b). Thus in order to obtain values of impedances and gain in equations (14.17), (14.20), (14.21), (14.22) and (14.23) we may write,

$h_{11}=h_{ib}$, short circuit input impedance in c.b. mode,

$h_{12}=h_{rb}$, open circuit reverse voltage transfer ratio in c.b. mode,

$h_{21}=h_{fb}$, short circuit forward current transfer ratio in c.b. mode,

$h_{22}=h_{ob}$, open circuit output admittance in c.b. mode.

For the common emitter (c.e.) amplifier h_{11}, h_{12}, h_{21} and h_{22} can be replaced by h_{ie}, h_{re}, h_{fe} and h_{oe} while for the common collector (c.c.) amplifier these can again be replaced by h_{ic}, h_{rc}, h_{fc} and h_{oc} respectively. Since the h parameters for c.e. and c.c. modes are not generally specified by the manufacturers, these are obtained by using the following relations:

$$\left.\begin{aligned}
h_{ie}&=\frac{h_{ib}}{1+h_{fb}}\\
h_{re}&=\frac{h_{ib}\,h_{ob}}{1+h_{fb}}-h_{rb}\\
h_{fe}&=-\frac{h_{fb}}{1+h_{fb}}\\
h_{oe}&=\frac{h_{ob}}{1+h_{fb}}
\end{aligned}\right\} \quad \ldots \quad (14.24)$$

$$\left.\begin{aligned}
h_{ic}&=\frac{h_{ib}}{1+h_{fb}}\\
h_{rc}&=1-\frac{h_{ib}\,h_{ob}}{1+h_{fb}}+h_{rb}\approx 1\\
h_{fc}&=-\frac{1}{1+h_{fb}}\\
h_{oc}&=\frac{h_{ob}}{1+h_{fb}}
\end{aligned}\right\} \quad \ldots \quad (14.25)$$

14.11.3 Comparison of c.b., c.e. and c.c. Amplifiers

It is seen that the equations for transistor performance can be applied suitably to all the three categories of transistor amplifiers; only the values of the parameters are to be changed depending on the circuit chosen. Equivalent circuits for common base, common emitter and common collector amplifiers with different *h*-parameter values are shown in Figs. 14.16(a), (b) and (c) respectively. Considering the

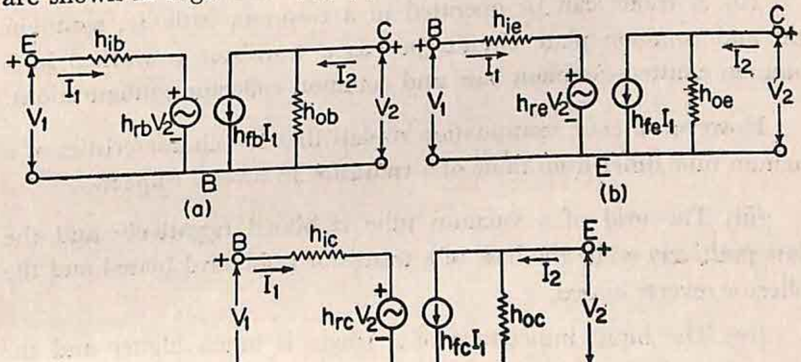


Fig. 14.16

mathematical relations we may draw the following conclusions given in Table 14.1 regarding the relative performance characteristics of the three modes of operation.

TABLE 14.1

Characteristics	c.b.	c.e.	c.c.
Impedance			
Input	lowest	intermediate	highest
Output	highest	intermediate	lowest
Gain			
Voltage	same as in c.e. mode	same as in c.b. mode	<1
Current	<1	$\gg 1$	$\gg 1$
Power		highest	

Out of the three, the common emitter amplifiers are most efficient and flexible in character and so they are frequently used while the other two types have applications only for specialized cases, such as for impedance matching or as a buffer stage.

14.12 Comparison between Vacuum Triode and Transistor

This comparison can be done by considering the following points:

(i) The cathode, grid and the plate terminals of a vacuum triode have similar functions as the emitter, base and collector terminals of a transistor.

(ii) A triode can be operated in a common cathode, common grid and common plate circuits just as a transistor is worked in a common emitter, common base and common collector configurations.

However, a close examination reveals that the characteristics of a vacuum tube differ from those of a transistor in several respects.

(iii) The grid of a vacuum tube is biased negatively and the plate positively while the base of a transistor is forward biased and the collector reverse biased.

(iv) The input impedance of a triode is much higher and the output impedance much lower in comparison to a transistor. Due to high input impedance a tube is voltage driven while because of its low input impedance a transistor must be current driven.

Examples

1. In a common base configuration with a base current of 0.05 m amps, the emitter current is 1 m amps. Calculate the value of the collector current.

We have, $I_E = I_B + I_C$

Here, $I_B' = 0.05$ m amps, $I_E = 1$ m amps

$\therefore$ the collector current, $I_C = I_E - I_B$

$= 0.95$ m amps.

2. Current amplification factor of a common base configuration is 0.88. Find the value of the base current, when the emitter current is 1 m amps.

If only d.c. values are considered then, $\alpha = \frac{I_C}{I_E}$

Here, $\alpha = \frac{I_C}{I_E} = 0.88$

and $I_E = 1$ m amps.

$\therefore$ $I_C = 0.88 \times 1 = 0.88$ m amps.

Now using the relation,

$I_E = I_B + I_C$

We get, $I_B = I_E - I_C$

$= 1 - 0.88 = 0.12$ m amps.

3. In a common base configuration, the voltage drop across a 2.2 K resistor which is connected in the collector is 2.2 V. Calculate the value of the base current. (given $\alpha = 0.9$)

We have. $I_C = \frac{2.2}{2.2} = 1$ m amps

and $\alpha = \frac{I_C}{I_E} = 0.9.$

$I_E = \frac{I_C}{\alpha}$

$= \frac{1}{0.9}$

$= 1.1.$

Using the relation,

$I_E = I_B + I_C$

We have, $I_B = I_E - I_C$

$= 1.1 - 1$

$= 0.1$ m amps.

4. A transistor having $h_{ie}=1100$ ohms, $h_{re}=2.5\times10^{-4}$, $h_{fe}=50$ and $h_{oe}=25$ micromhos is connected as a common emitter amplifier with the load resistance $R_L=1000$ ohms. Calculate the current gain and the input impedance.

Here, $h_{ie}=1100 \text{ ohms}=h_{11}$,

$h_{re}=2.5\times10^{-4}=h_{12}$,

$h_{fe}=50=h_{21}$,

$h_{oe}=25$ micromhos

$=25\times10^{-6} \text{ mhos}=h_{22}$;

and $R_L=1000$ ohms.

Now, current gain

$$A_i=\frac{h_{21}}{h_{22}R_L+1}$$

$$=\frac{50}{25\times10^{-6}\times10^{3}+1}$$

$$=\frac{50}{1.025}=48.8.$$

Input impedance,

$$R_{in}=\frac{\Delta h\, R_L+h_{11}}{h_{22}R_L+1}$$

where $\Delta h=h_{11}h_{22}-h_{12}h_{21}$

$=1100\times25\times10^{-6}-2.5\times10^{-4}\times50$

$=150\times10^{-4}$

$$\therefore \quad R_{in}=\frac{150\times10^{-4}\times10^{3}+1100}{1.025}$$

$$=\frac{1115}{1.025}=1088 \text{ ohms}.$$

5. A junction transistor has the following specifications: $h_{ib}=40$ ohms, $h_{rb}=4\times10^{-4}$, $h_{fb}=-0.98$ and $h_{ob}=10^{-6}$ mhos. Calculate the maximum available power gain of the transistor.

The power gain,

$$A_p=-\frac{h_{21}^2 R_L^1}{(R_L\Delta h+h_{11})\,(1+h_{22}R_L)}$$

$$=-\frac{h_{21}^2}{\left(\Delta h+\frac{h_{11}}{R_L}\right)(1+h_{22}R_L)}$$

For maximum power gain we differentiate A_p with respect to R_L and equate the result to zero. Thus,

$$\frac{dA_p}{dR_L}=-h_{21}^2\,\frac{(\Delta h+h_{11}/R_L)h_{22}-(1+h_{22}R_L)h_{11}/R_L^2}{[(\Delta h+h_{11}/R_L)\,(1+h_{22}\,R_L)]^2}=0$$

or,
$$\left(\Delta h+\frac{h_{11}}{R_L}\right)h_{22}=\frac{h_{11}}{R_L^2}+\frac{h_{11}\,h_{22}}{R_L}$$

or,
$$R_L^2=\frac{h_{11}}{\Delta h\,.\,h_{22}}$$

So the maximum power gain,

$$A_{p_{max}}=-\frac{h_{21}^2}{\left[\Delta h+h_{11}\left(\dfrac{\Delta h\,h_{22}}{h_{11}}\right)^{1/2}\right]\left[h_{22}\left(\dfrac{h_{11}}{\Delta h\,h_{22}}\right)^{1/2}+1\right]}$$

$$=-\frac{h_{21}^2\,(\Delta h)^{1/2}}{(\Delta h)^{1/2}[(\Delta h)^{1/2}+(h_{11}h_{22})^{1/2}]\,[(h_{11}h_{22})^{1/2}+(\Delta h)^{1/2}]}$$

$$=-\frac{h_{21}^2}{[(\Delta h)^{1/2}+(h_{11}\,h_{22})^{1/2}]^2}$$

In the given problem,

$h_{ib}=40$ ohms$=h_{11}$,

$h_{rb}=4\times10^{-4}=h_{12}$,

$h_{fb}=-0.98=h_{21}$,

and $h_{ob}=10^{-6}$ mhos$=h_{22}$.

Here,
$$\Delta h=h_{11}h_{22}-h_{12}h_{21}$$
$$=40\times10^{-6}+4\times10^{-4}\times0.98$$
$$=432\times10^{-6}.$$

$$\therefore\quad A_{p_{max}}=-\frac{(-0.98)^2}{[(432\times10^{-6})^{1/2}+(40\times10^{-6})^{1/2}]^2}$$
$$=-1307$$

So the maximum power gain is 1307.

Self-Test

Read each of the following and provide the appropriate words:

(a) In 1948, while working at the Bell Telephone Laboratories, — and — announced the development of the first transistor.

(b) Transistors are formed usually by germanium and —.

(c) A transistor has three internal electrodes known as —, — and —.

(d) The common — is frequently used as it provides suitable voltage, current and power gain.

(e) The curve obtained on plotting — against — keeping V_{CB} as parameter is called the input characteristic.

(f) In transfer characteristics, values of — is plotted against —.

(g) The three sets of parameters used to analyse transistor circuits are — parameters, — parameters and — parameters.

(h) The input impedance of common — amplifier is lowest.

(i) The power gain of common emitter amplifier is —.

(i) The base of a transistor is — biased and the collector — biased.

(k) The cathode, grid and plate of a triode have similar functions as the —, — and — terminals of a transistor.

Review Questions

1. What is a transistor?

2. Classify the different types of transistors.

3. Draw the symbols of *P–N–P* and *N–P–N* transistors.

4. Discuss how the leads of a transistor can be identified.

5. Briefly discuss the manufacturing methods of transistors.

6. Define α and β of a transistor.

7. Show that $\beta = \frac{\alpha}{1-\alpha}$.

8. Explain the different characteristics of a transistor under common base and common emitter configurations.

9. What do you understand by transistor biasing. Explain the biasing arrangement for a transistor amplifier under common emitter configuration.

10. Derive expressions for input impedance, output impedance, voltage gain and power gain of a common emitter transistor amplifier.

11. Make a comparative study of common base, common emitter and common collector transistor amplifiers.

12. Make a comparative study between a vacuum triode and a transistor.

13. Determine the current amplification factor of a common base configuration when $I_B = 0.05$ m amps and $I_C = 0.95$ m amps. (*Ans.* 0.95)

14. For a transistor $\beta = 50$ and $I_B = 20\ \mu$A, find the value of I_E. (*Ans.* 1.02 m amps)

15. In a common base connection with $\alpha=0.92$ the emitter current is 1 m amp. But if the emitter circuit is open the collector current shows 40 μ amps. Calculate the total collector current. (*Ans.* 0.96 m amps)

16. The hybrid parameters of a transistor used as an amplifier in the c.e. configuration are: $h_{11}=800\ \Omega$, $h_{21}=46$, $h_{22}=80\times10^{-6}$ mhos and $h_{12}=5.4\times10^{-4}$. If the load resistance is 5 KΩ and the effective source resistance 500 Ω, calculate the voltage and current gains and the output resistance. (*Ans.* -231; 32.9; 16.4 KΩ)

17. A junction transistor has the following hybrid parameters when used in the c.e. configuration: $h_{11}=800\ \Omega$, $h_{22}=80\times10^{-6}$ mhos, $h_{12}=5\times10^{-4}$ and $h_{21}=48$. It is used in this configuration as an amplifier with a load resistance of 8 KΩ. If the source has an e.m.f. of 100 mV., and an internal resistance of 500 Ω, calculate the power developed in the load. (*Ans.* 2.08 mW)

18. The common emitter hybrid parameters of a transistor are $h_{ie}=800$ ohm, $h_{fe}=47$, $h_{oe}=80$ μmhos and $h_{re}=5\times10^{-4}$. Calculate the output voltage and output resistance for a c.e. voltage amplifier using this transistor with a load of 5 KΩ and a 10 mV source of internal resistance 500 Ω. (*Ans.* 1.38V; 3.82 KΩ)

19. The common emitter hybrid parameters of a junction transistor are given as follows: $h_{11}=1500$ ohms, $h_{12}=10^{-4}$, $h_{21}=50$ and $h_{22}=10^{-5}$ mhos. Calculate the parameter values for the *T*-equivalent circuit of this transistor. Also determine the input impedance and current gain of a single stage common emitter amplifier using this transistor and having a collector load of 5 KΩ.

(*Ans.* $r_e=10\ \Omega$, $r_b=1$ KΩ, $r_c=5$ MΩ, $\alpha=0.98$; 1476 Ω, 47.6)

CHAPTER 15

FIELD-EFFECT TRANSISTORS

15.1 Introduction

The transistors we have discussed earlier are known as bipolar transistors, since they have two junctions and their operations depend on the action of two different types of charge carriers; electrons and holes. There is another class of transistors whose action depends on only one type of charge carrier. Such unipolar devices are known as field-effect transistors (FETs). FETs are of two distinct types : (i) the junction type (JFET) and (ii) the metal-oxide semiconductor type (MOSFET).

The FET differs from the bipolar transistor in the following important characteristics:

(i) It is easier to fabricate and takes less space in integrated form.

(ii) It has a high input impedance of the order of many megohms.

(iii) It shows no offset voltage at zero drain current.

(iv) Its operation depends only on the flow of the majority carriers and hence it is a unipolar device.

(v) Its noise is less than bipolar transistor.

15.2 JFET

An *N*-channel JFET is illustrated in Fig. 15.1. The three elements of the transistor are the source, the gate, and the drain. These correspond respectively the emitter, the base, and the collector of a bipolar transistor. In the figure, the body or channel of the transistor is an *N*-type semiconductor while the gate embedded on both sides of the

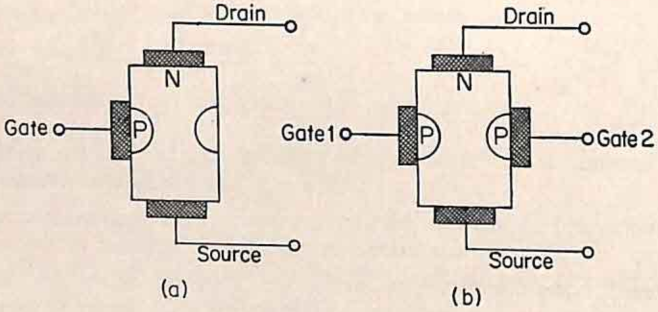


Fig. 15.1

channel, is the *P*-type material and hence the name junction FET. When gates 1 and 2 are internally connected, it is called a single gate FET (Fig. 15.1a). When separate leads are brought out for gates 1 and 2, the device is known as a dual gate FET (Fig. 15.1b). The FET thus constructed is an *N*-channel, *P*-gate device the symbol of which is shown in Fig. 15.2. Similarly it is also possible to make a *P*-channel, *N*-gate JFET whose symbol is presented in Fig. 15.3. It is to be noted that for an *N*-channel device the gate arrow points towards the channel while for a *P*-channel the arrow points away from the channel. For both the types the gate arrow may be centred on the channel or close to the source.

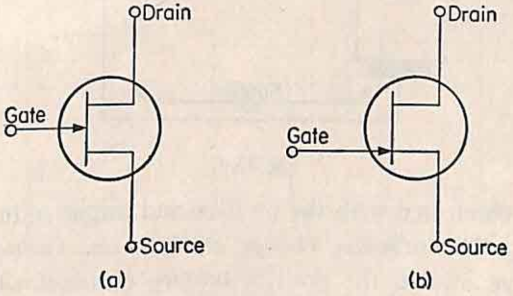


Fig. 15.2

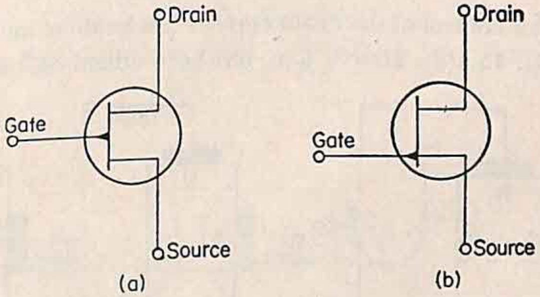


Fig. 15.3

15.2.1 Operation

The operation of a unipolar transistor is usually different from those of a bipolar transistor. The main difference is that, in a JFET, the drain currrent (I_D) is controlled by gate to source voltage (V_{GS}) while in a bipolar transistor the collector current is controlled by base current.

In order to explain the operation of a JFET, let us consider Fig. 15.4, where the drain and source of the *N*-channel semiconductor are respectively connected with the positive and negative terminals of the battery V_{DD}. The negative charge carriers, i.e., electrons in the *N*-channel move toward the positive battery terminal while electrons from its negative terminal move into the *N*-channel. This movement of the electrons is done through the source to replace those that left at the drain. Current will continue to flow as long as the circuit is complete and this can be controlled slightly by varying V_{DD}.

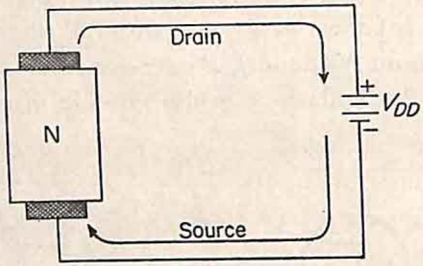


Fig. 15 4

A further control of the drain current can be done more effectively by using Fig. 15.5(a). Here a gate has been added and a reverse-bias is applied to it with respect to the source. By negative biasing the gate, the electric field at the junction has the effect of widening the gate and thus reducing the channel width as in Fig. 15.5(b). If the reverse-bias is made high enough the gate becomes so wide that the channel is blocked and hence the drain current is completely cut off, as shown in Fig. 15.5(c).

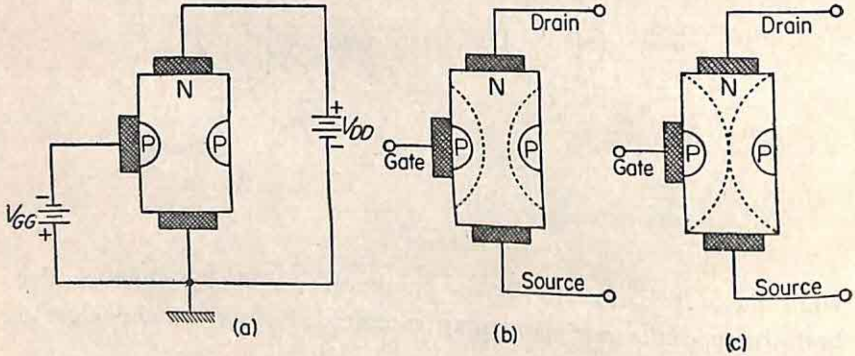


Fig 15.5

15.2.2 Characteristics

The curve obtained by plotting drain current (I_D) along the Y-axis against drain-to-source voltage (V_{DS}) along the X-axis for fixed gate bias voltage (V_{GS}) is called the drain characteristic of a JFET. The circuit diagram for stuyding the characteristic curves of a JFET is shown in Fig. 15.6. In the figure, V_{GG} is used as the gate bias supply and V_{DD} as the drain voltage source. The voltmeter (V) measures the drain-to-source voltage (V_{DS}) and the milliammeter measures the corresponding drain current (I_D).

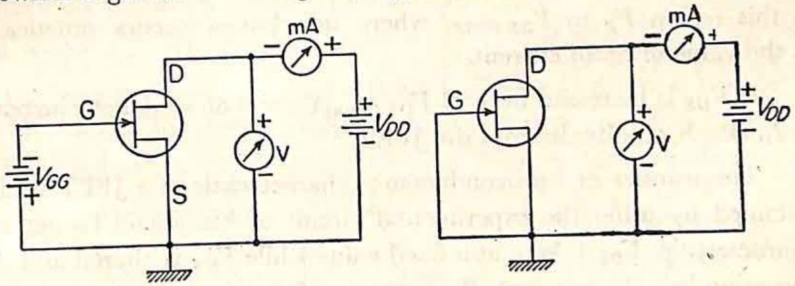


Fig. 15.6

The variation of I_D with V_{DS} for fixed V_{GS} is shown in Fig. 15.7. A group of such drain characteristic curves have been drawn by setting V_{GS} at different fixed values. V_{GS} may be made increasingly negative until I_D cutoff is reached which is nearly -2 V in the figure. This value

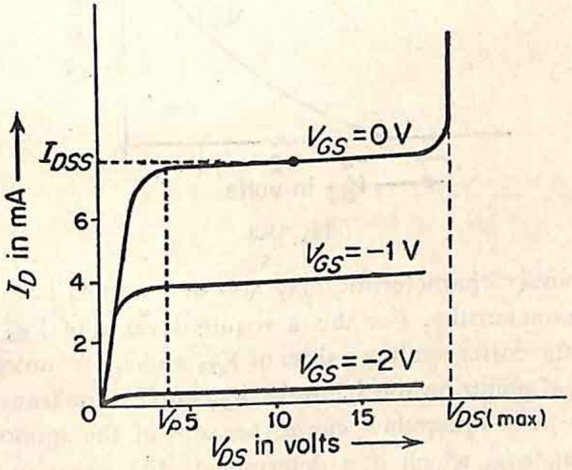


Fig. 15.7

of V_{GS} is known as V_{GS} off. It is noted that as V_{DS} is gradually increased from zero to V_P, the value of I_D increases from zero to I_{DSS}. The voltage V_P is called the pinchoff voltage and I_{DSS} is the maximum drain current that can be attained without destroying the JFET. As V_{DS} increases from V_P to $V_{DS(max)}$ the drain current remains almost constant at the value of I_{DSS}. JFET when used in a circuit is operated in this region V_P to $V_{DS\,(max)}$ where no change occurs practically in the value of drain current.

If V_{DS} is increased beyond $V_{DS\,(max)}$ there is an avalanche increase in I_D which rapidly destroys the JFET.

The transfer or transconductance characteristic of a JFET is also obtained by using the experimental circuit of Fig. 15.6. To get the characteristic, V_{DS} is kept at a fixed value while V_{GS} is altered and the corresponding I_D is noted. The nature of the transfer characteristic curve of a JFET is shown in Fig. 15.8.

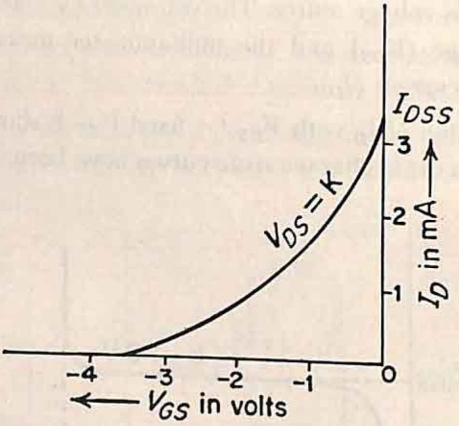


Fig. 15.8

The transfer characteristic may also be obtained from the family of drain characteristics. For this a required value of V_{DS} is selected first. Then the corresponding values of V_{GS} and I_D are noted to get the coordinates of points on the I_D versus V_{GS} curve. The transfer curve is also known as a square-law curve, because of the squared term in the equation from which it is determined. The equation relating I_D and V_{GS} may be expressed as,

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS\ off}}\right)^2 \qquad \ldots \qquad (15.1)$$

15.2.3 Applications

Because of the square-law characteristics, FETs are frequently used in the tuners of radio and TV receivers. Further, in a FET since the gate draws no current, it has a very high input impedance which is suitable in electronic voltmeters. Voltmeters designed with FETs in the input are popularly called FETs meters.

15.2.4 JFET Biasing

The gate biasing network of a JFET is similar to the base-biasing network of a bipolar transistor with a difference that the JFET gate is reverse-biased while the bipolar transistor base is forward-biased.

(a) **Voltage-divider Bias**

An *N*-channel JFET voltage divider gate bias arrangement is shown in Fig. 15.9(a). The voltage at the gate to ground is given by,

$$V_G=\frac{R_1}{R_1+R_2}V_{DD} \qquad \ldots \qquad (15.2)$$

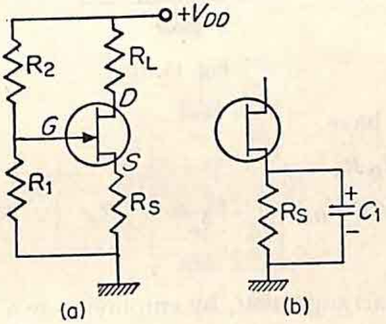


Fig. 15.9

While the voltage on the source to ground is,

$$V_S=I_D R_S \qquad \ldots \qquad (15.3)$$

where, I_D=drain current,

R_S=source resistor.

The gate bias V_{GS} is now obtained by subtracting V_S from V_G

i.e., $$V_{GS}=V_G-V_S \qquad \ldots \qquad (15.4)$$

In order to ensure reverse bias of the gate, the parameters in the circuit are chosen in such a manner that V_{GS} becomes a negative quantity. That is V_S on the right hand side of equation (15.4) must always be greater than V_G. By using a bypass capacitor C_1, as shown in

Fig. 15.9(b), the degenerative signal voltage developed across R_S can be eliminated.

(b) Self Bias

To explain the self bias for an *N*-chennel JFET, a simple circuit is drawn in Fig. 15.10. Since the gate through the resistor R_1 is returned to ground and there is no gate current, the voltage on the gate V_G is zero.

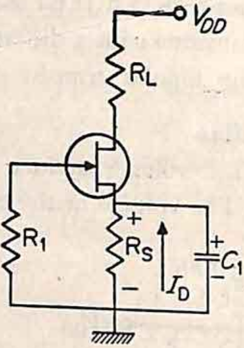


Fig. 15.10

As before, we have,

$$V_S = I_D R_S \quad \ldots \quad (15.5)$$

So the gate bias, $V_{GS} = 0 - V_S = -I_D R_S \quad (\because V_G = 0) \quad \ldots \quad (15.6)$

(c) Source Bias

A source bias arrangement, by employing two independent power supplies are shown in Fig. 15.11. Here V_{DD} is the drain supply and V_{SS} is the source supply. The parameters in the circuit are chosen to supply the proper gate bias for the required drain current.

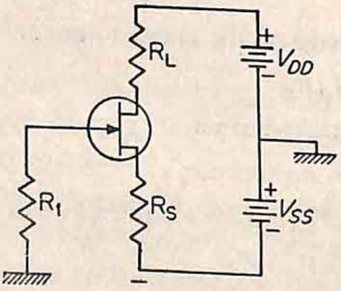


Fig. 15.11

15.3. MOSFET

Like JFET, just discussed, the MOSFET is also a field effect transistor of much higher input impedance than the JFET. Depending on the manner of construction MOSFETs are mainly classified into two different types: (i) Enhancement type and (ii) Depletion type.

MOSFETs have some added advantages. These are: (a) lower noise (2 to 6 dB typical), (b) reduced cross modulation effects, (c) low feedback capacitance (0.02 to 0.17 pF typical), (d) high transconductance (upto 15,000 micromhos typical), and (e) high maximum operating frequency (upto 500 MHz, depending upon the model).

The only pronounced disadvantage of the MOSFET is the delicateness of its gate insulation.

15.4 Enhancement-type MOSFET

The construction of an enhancement type MOSFET is shown in Fig. 15.12. In the enhancement type there is no channel between the source and the drain but separating the *N*-type source and drain is a *P*-type substrate. A very thin, fragile layer of silicon dioxide (SiO_2) is deposited over the substrate. On the silicon dioxide insulator a metallic film is deposited which serves the purpose of the gate. Usually there are four ohmic contacts, one each for the source, drain, substrate and the gate. But sometimes the substrate is internally connected to the source and so no substrate lead is required then.

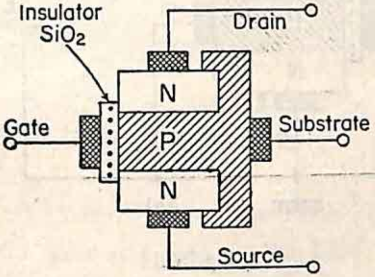


Fig. 15.12

Since the gate is insulated from the body of the FET the MOSFET is also called an insulated gate FET (IGFET). Although no physical channel is there, the MOSFET is sometimes termed as *N*-channel enhancement type FET.

It may be noted that a *P*-channel normally off MOSFET may be constructed by using *P*-type source and drain and *N* substrate. The symbols for both *N*- and *P*-types are shown in Fig. 15.13.

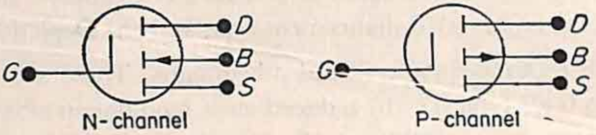


Fig. 15.13

15.4.1 Operation

From the manner of construction it is clear that in a MOSFET the gate and the substrate behave as the two plates of a capacitor separated by an insulator of SiO_2. As shown in Fig. 15.14(a), when a positive voltage is applied to the gate relative to the source to which the substrate is also connected, the capacitor begins to charge. Since the gate is made positive, negative charges appear in the substrate between drain and source [Fig. 15.14(b)], in effect creating an *N*-channel which will allow to flow current in the source-to-drain circuit. The MOSFET thus conducts only if the gate is made positive relative to the source and it is cut off when the gate-to-source voltage is zero. For this reason it is called a normally off MOSFET.

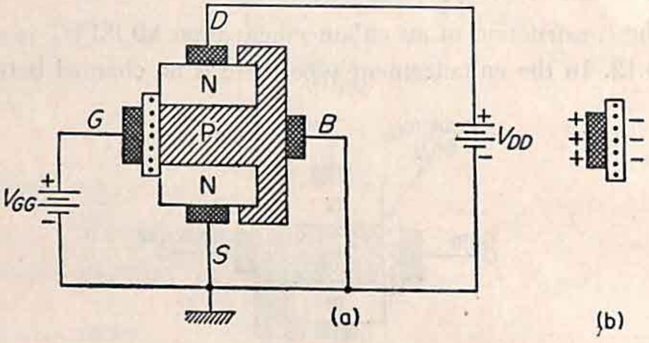


Fig. 15.14

15.5 Depletion-type MOSFET

The construction of a depletion type MOSFET is shown in Fig. 15.15. The manner of construction of depletion MOSFET is similar to that of an enhancement-type with one exception. The depletion

MOSFET, as evident from the figure, has an *N*-channel while the enhancement-type has not.

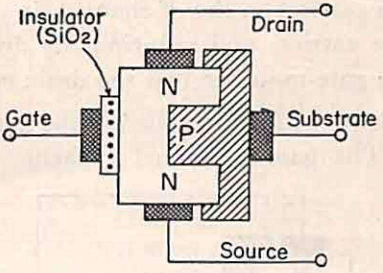
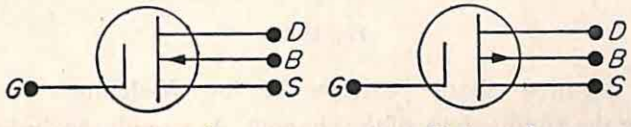


Fig. 15.15

The depletion MOSFET may also be constructed using a *P*-channel and *N* substrate. The symbols for both *N*- and *P*-channel depletion MOSFETs are shown in Fig. 15.16. As the depletion MOSFET is normally on, the vertical channel line is not broken here as in the enhancement-type.



N-channel P-channel

Fig. 15.16

15.5.1 Operation

The FET in Fig. 15.15 can be operated with both negative and positive gates. When the gate is negative, the FET operates in the depletion mode and when positive operates in the enhancement mode.

Let us first consider the case when the gate is made negative relative to the source. The circuit arrangement is shown in Fig. 15.17

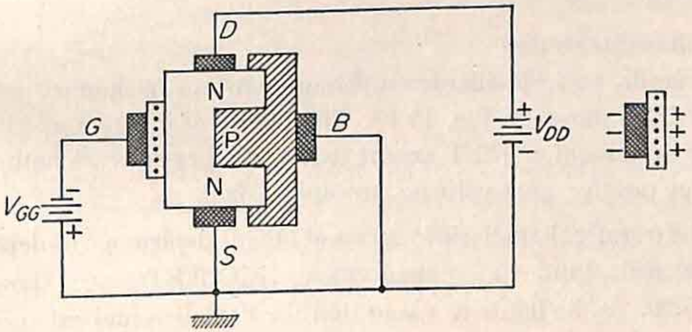


Fig. 15.17

including the capacitor charge distribution on the gate and *N*-channel. When the negative voltage is applied to the gate, electrons on it repel the negative charge carriers in the *N*-channel, in effect depleting the channel of negative carriers and reducing the drain current. For a sufficiently negative gate-to-source bias the drain current is cut off.

Let now a positive voltage is applied to the gate of the *N*-channel as in Fig. 15.18. The gate-to-channel capacitor begins to charge, inducing negative charge carriers in the *N*-channel and hence increasing the conductivity of the channel. As a result the drain current increases. The more the positive voltage is applied to the gate, the more the drain current flows. Thus the enhancement mode works.

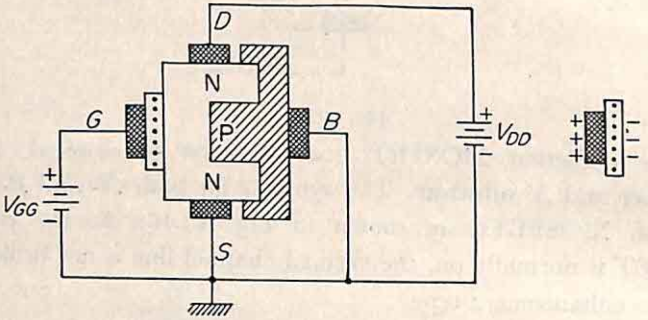


Fig. 15.18

When the gate voltage is zero, i.e., the gate is shorted to the source but the voltage source V_{DD} is connected as in Fig. 15.17, drain current will flow as usual from source-to-drain. However, the drain current is now less than it was with positive voltage. Since the drain current flows even with no gate voltage, this is a normally on MOSFET.

15.6 Characteristics

A family of drain characteristic curves for an *N*-channel practical MOSFET is shown in Fig. 15.19. The nature of the characteristics is similar to those of a JFET except that in the present case both negative and positive gate voltages are operational.

The transfer characteristic curves of the (a) depletion, (b) depletion-enhancement and (c) enhancement MOSFETs are shown in Fig. 15.20. In the figure it is seen that the depletion and enhancement regions represent respectively for negative and positive values of V_{GS}.

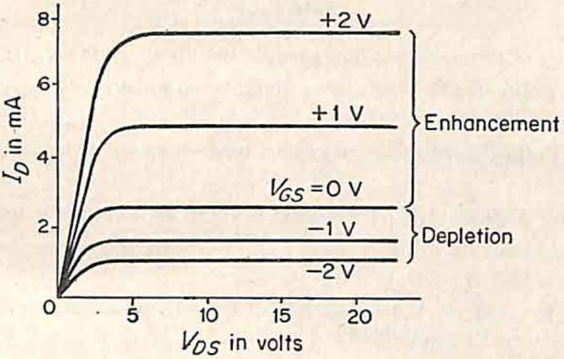
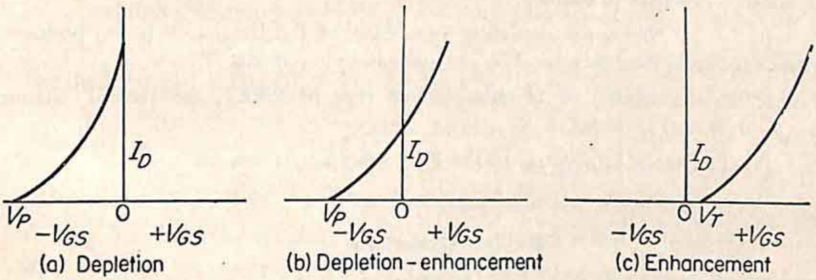


Fig. 15.19

The figures (a), (b) and (c) clearly show that except for lateral displacement all the three transfer characteristics are quite similar.



(a) Depletion (b) Depletion - enhancement (c) Enhancement

Fig. 15.20

The point V_T in Fig. 15.20(c) is called the gate-source threshold voltage from which the drain current I_D begins to rise, i.e., the current passes between source and drain. This value of V_T is very important for all practical purposes and so it is usually given on the manufacturer's specification sheet. Various techniques have been applied to reduce the threshold voltage since a low value of V_T allows (i) smaller switching time, (ii) higher packing densities, (iii) small power supply voltage and (iv) campatible operation with bipolar devices.

15.7 MOSFET Biasing

In biasing MOSFETs we may use the voltage-divider bias, self bias or the source bias, as in JFET, with similar circuit arrangements. The polarity of the bias required will depend on the type of MOSFET (enhancement or depletion) and on the nature of the channel (*N or P*).

Self-Test

Read each of the following and provide the appropriate words:

(a) The drain characteristic of a unipolar transistor corresponds to the — characteristic of a bipolar transistor.

(b) The drain characteristic represents how — varies with — when — is kept constant.

(c) In the *N*-channel JFET the gate is made by — type semiconductor.

(d) Maximum safe drain current I_{DSS} is found when the — is shorted to the source.

(e) The pinchoff voltage V_P represents the voltage on the drain at which the drain current is—(cut off/stabilised).

(f) From V_P to V_{DS} max, the value of I_D remains —.

(g) In an enhancement type MOSFET there — (is/is not) a physical channel between the source and the drain.

(h) To permit current flow the gate of an enhancement type MOSFET is to be biased — relative to source.

(i) In an *N*-channel depletion type MOSFET if the gate is biased positively relative to the source, then the FET operates in the — mode.

(j) In the symbol of an enhancement type MOSFET, the vertical channel line — (is/is not) broken.

(k) The input impedance of the FET amplifier is very —.

Review Questions

1. What are the advantages of a FET over a bipolar transistor?

2. Discuss the basic structure of an *N*-channel JFET. Draw its circuit symbol.

3. Draw the drain characteristics and transfer characteristics of a JFET. Qualitatively explain the shape of these characteristics.

4. Discuss with circuit symbols the construction of the enhancement and depletion type MOSFET.

5. Draw the characteristic curves of the two different types of MOSFETs. What is threshold voltage?

CHAPTER 16

INTEGRATED CIRCUITS

16.1 Introduction

Integrated circuits abbreviated as ICs have radically changed the world of electronics. The application of these microelectronic 'giants' was first felt in the field of computer technology. The first-generation electronic computers used vacuum tubes which were replaced by transistors in second generation computers while the third generation computers used digital ICs, increasing computer speed and reliability and at the same time reducing its size considerably.

Now-a-days integrated circuits are widely employed in linear circuits, in communications, military and also in industrial applications.

16.2 Principle of Integrated Circuit

Semiconductor properties are utilized for producing an entire electronic circuit within a single crystal. Such a circuit reduces considerably the number of individual components in complex electronic circuits.

The basis for the integrated circuit development is very simple. Silicon made electronic components of various types, such as, transistors, diodes, resistors, etc. having suitably disposed *N*-type and *P*-type regions are combined in a single crystal slab. The stray coupling due to junction capacitances is taken into consideration in designing the circuit. In fact, the capacitance of a *P-N* junction may serves the purpose of a capacitor in an IC. However, for most of the cases the capacitors and also inductors are connected externally as separate components.

16.3 Fabrication of Monolithic IC

The term 'monolithic' comes from two Greek words, *monos* (meaning single) and *lithos* (meaning stone). A monolithic integrated circuit, as the name implies, is thus built into a single stone or a single crystal.

Integrated circuit (IC) is not just an efficient transistor or several transistors placed inside a small case. Rather it is a complete curcuit consisting of active and passive components. The active components are transistors and diodes while the passive elements are capacitors and resistors. IC is formed by an intricate microphotolithographic process usually on a silicon chip and housed in a container no larger than a small transistor.

The fabrication processes of IC are based on the production technology of silicon-diffused or 'planar' transistor. Silicon ICs are fabricated on a silicon disk the diameter of which is approximately 1 inch and about the thickness of this paper. The disk is altered in a series of individual steps. The top of the disk is first oxidized and then covered with a photosensitive lacquer, as a 'resist'.

Next microphotolithographic process is applied to etch the circuit patterns into the oxides. After heating, a very small quantity of impurity, like boron or arsenic, are diffused into the silicon in order to form *P* and *N* islands on the disk. This process is repeated several times untill all the circuit components are made on the disk. The components are then connected by depositing vaporized aluminium in the desired pattern. These are now diced. The chips are separated and mounted on ceramic or metal bases. Then thin aluminium wires, about one-third the thickness of the human hair, are bounded between the IC contacts and the header leads and then the package is sealed properly. In general, (*a*) flatpack, (*b*) dual-in-line package or (*c*) transistor type TO-5 case are used as shown in Fig 16.1

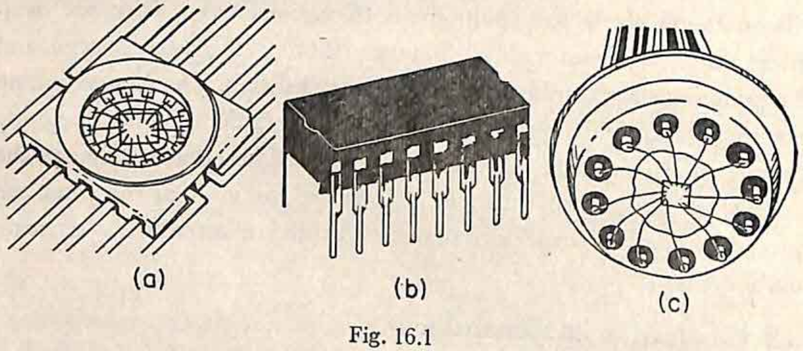

(a) (b) (c)

Fig. 16.1

ICs are economically feasible as they are manufactured simultaneously in large quantities.

16.4 Classification

There are many IC configurations or circuits. However, they are broadly classified under two heads—linear ICs and digital ICs. Mainly linear ICs are used in signal-processing circuits (amplifiers, oscillators etc), in communication electronics (TV, radio receivers, transmitters etc.) and in hi-fi equipments while digital ICs are used in calculators, computers and other electronic 'counting' devices.

16.4.1 Advantages of an IC

In comparison to a circuit of discrete components an integrated circuit has the following advantages:

(i) Low cost, due to a large number produced at a time,
(ii) High reliability as there are no soldered joints,
(iii) Small size,
(iv) Improved performance.

16.5 Circuit Configurations (Linear ICs)

Perhaps the concept of ICs first came from the printed-circuit techniques and the diffused planar-transistor-fabricating technology. In fact, the earlier designs of ICs well resembled transistor circuits using discrete components. With the increase of knowledge, however, ICs have taken a completely unique character.

Active components are less costly in an IC as they take comparatively little space than the passive elements. Inductors are not fabricated in an IC. So integrated circuit RC rather than LC 'tuning' is used. Chips are so designed that they may be used in more than one circuit configuration. As for example, the same IC CA 3018, containing an array of four transistors with 12 external connections, has been utilized in different external circuit arrangements. Fig. 16.2 shows two such arrangements where it has been used as (i) wideband amplifier (Fig. 16.2a) and (ii) RF amplifier (Fig. 16.2b). The transistors in this IC, used as discrete components, are labeled as Q_1, Q_2, Q_3

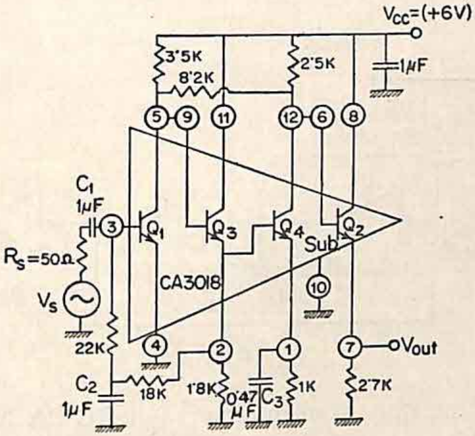


Fig. 16.2(a)

and Q_4. External connections are brought to the 12 IC terminals, numbered 1 through 12 and power is supplied from a +6 V source.

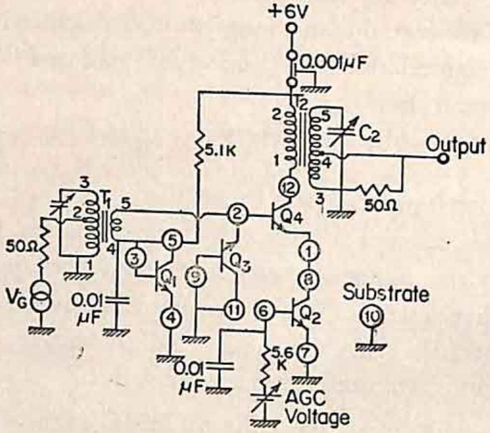


Fig. 16.2(b)

We may mention the name of another IC CA 3020 which is described by the manufacturer as a "Monolithic integrated circuit, a multipurpose, multifunction power amplifier designed for use in portable and fixed audio communication equipment and servo control

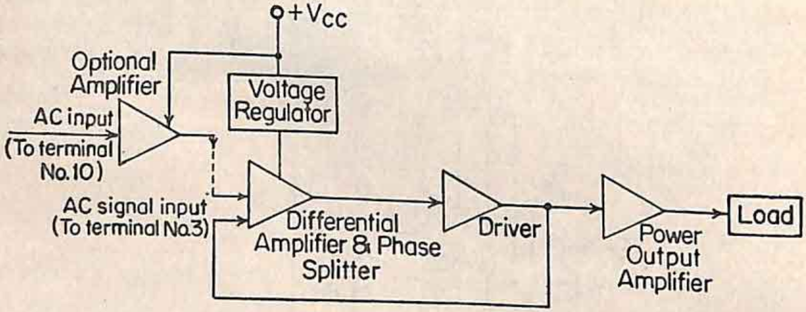

+Vcc
Optional Amplifier
AC input (To terminal No.10)
Voltage Regulator
AC signal input (To terminal No.3)
Differential Amplifier & Phase Splitter
Driver
Power Output Amplifier
Load

Fig. 16.3(a)

systems." The functional block diagram of the IC CA 3020 is drawn in Fig 16.3(a) while an audio amplifier using the IC is shown in Fig. 16.3(b).

16.6 Digital ICs

Digital integrated circuits are also known as logic circuits, because the characteristics of the circuit and the nature of the inputs determine the output. Or in other words, the logic of the circuit ensures a predetermined output for specific inputs when the input combination is correct for that particular circuit.

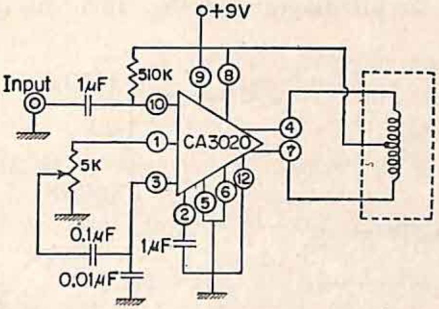


Fig. 16.3(b)

Computer designs are of two-state type, i.e., either Yes or No variety. Logic circuits can be in one of the two positions, such as HIGH or LOW, ON or OFF. The two-position nature of computer circuits gives information by a d.c. level on a signal line; the presence of information is indicated by a positive voltage level while the absence by a negative level. These levels are also called as UP (positive) and DOWN (negative) levels.

16.6.1 AND Circuit and its Truth Table

An AND circuit is shown in Fig 16.4(a) while Fig 16.4(b) gives its symbolic representation. This is a simple logic circuit using diodes.

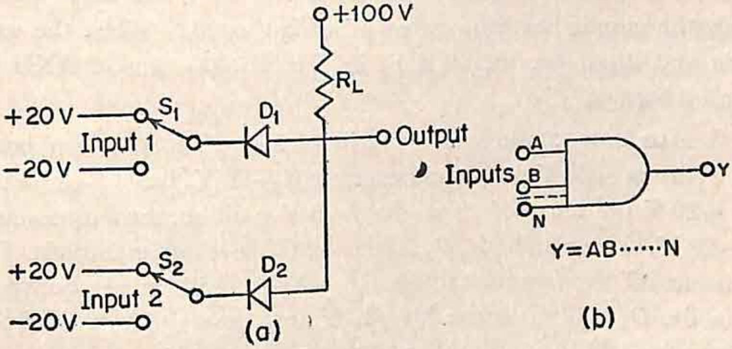


Fig. 16.4

In such a circuit both the inputs must be at an UP level to produce an UP level at the output. In the figure, D_1 and D_2 are two diodes, each receives an independent input signal voltage (+20 V or −20 V) through S_1 and S_2 respectively.

To understand the operation of an AND circuit let us consider first the simple circuit diagram of Fig. 16.5. As shown, when the switch S_1 is in −20 V position, circuit is completed from the −20 V source through diode D_1 and resistor R_L to the +100 V source. Under such condition, since D_1 is forward biased it conducts. As the forward resistance of D_1 is low compared with the load resistance, a negligible voltage drop appears across D_1. Therefore with respect to common ground the output level exhibits −20 V. Similarly, when the switch is placed in the +20 V position, output voltage exhibits +20 V.

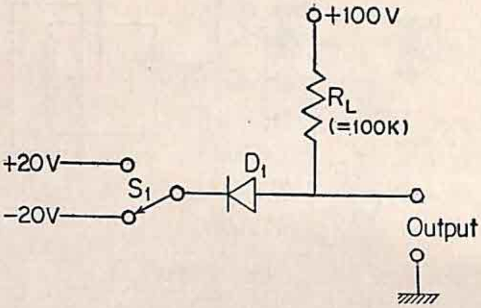


Fig. 16.5

The use of one diode in a circuit is therefore just to transfer either input level to the output. That is why with only one diode and one input, the circuit has little value as a logic circuit. When the second diode and input are included as in Fig. 16.4(a), a real AND logic circuit is formed.

Let us now consider the circuit of Fig. 16.4(a). When both S_1 and S_2 are at −20 V position, the output is −20 V. But if S_1 is placed in the +20 V position and S_2 in the −20 V position, the output remains at −20 V, since the diode D_2 has a −20 V level on its cathode. Diode D_1 is cut off because its cathode is +20 V and is more positive than its anode. D_1 is thus reverse biased. If next the switches S_1 and S_2 are both set in +20 V position, the output gives +20 V.

From the measurement of the output of an AND circuit we can therefore draw the following logical conclusions:

(i) If the output is UP, then both the inputs must be UP.

(ii) If the output is DOWN, then either or both the inputs must be DOWN.

TRUTH TABLE

Usually the logic of digital circuits is given in the form of a truth table. A digital UP state is represented in convention by the binary 1 while a DOWN state by the binary number 0. All the necessary conditions in a two-input AND circuit are then given in Table 16.1.

TABLE 16.1: AND Truth Table

Inputs		Output
A	B	Y
0	0	0
1	0	0
0	1	0
1	1	1

16.6.2 OR Circuit and its Truth Table

The OR circuit is another logic circuit. Such a circuit provides an UP level at the output when any one of its inputs has an UP level. It is, however, similar to the AND circuit with a difference that the polarity of the diodes is reversed and the load resistance R_L is connected to the negative voltage source. Fig. 16.6(a) shows an OR circuit while Fig. 16.6(b) is its symbolic representation.

To understand the operation of an OR circuit, for the time being, let us consider that only the diode D_1 is present in the circuit of Fig. 16.6(a). When the input to D_1 is −20 V, the diode becomes

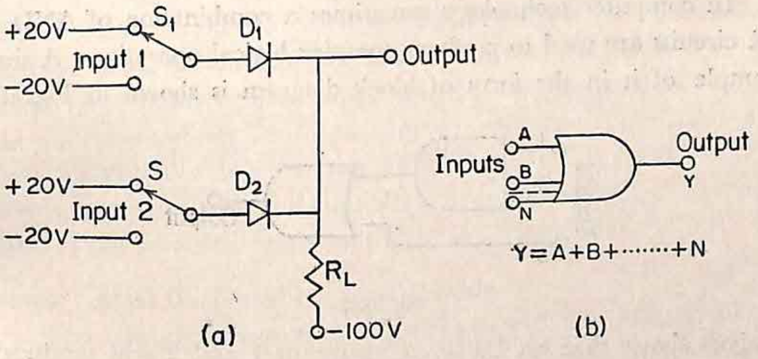


Fig. 16.6

forward biased since the anode is less negative than the cathode which is connected through the load resistor to the −100 V source. The diode D_1 thus conducts and it acts as a low resistance switch. A very small voltage therefore drops across D_1 as compared to that across R_L. The output level so exhibits −20 V. Similarly when the switch S_1 is placed to +20 V position, the output will exhibit +20 V.

Now, if both the diodes are connected and the inputs are at −20 V position, the output is −20 V. But if either D_1 or D_2 has +20 V on its input, the output is +20 V.

From the measurement of the output of an OR circuit we can, therefore, draw the following logical conclusions:

(i) If the output is DOWN, then both the inputs must be DOWN,

(ii) If the output is UP, then either or both the inputs must be UP.

Truth Table

All the possible conditions in a two-input OR circuit are given in Table 16.2.

TABLE 16.2: OR Truth Table

Inputs		Output
A	*B*	*Y*
0	0	0
1	0	1
0	1	1
1	1	1

16.6.3 Combined AND–OR Circuits

In computer technology sometimes a combination of AND and OR circuits are used to perform complex logical operations. A simple example of it in the form of block diagram is shown in Fig. 16.7.

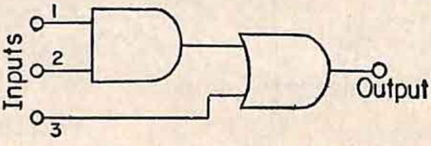


Fig. 16.7

Analysis shows that an UP level on inputs 1 and 2 will produce an UP level on input 3 alone produces an UP level at the output.

16.6.4 AND and OR Gates

AND and OR circuits are also known as Gates. In digital electronics, a gate is a circuit which has two or more inputs and one output. The nature of the gate and input combinations determine the output, i.e., either UP (1) or DOWN (0).

16.6.5 NOT Circuit

A NOT circuit is nothing but an inverter, mathematically the characteristic of which is given in equation (16.1).

$$\text{If } V_{in}=A, \text{ then } V_{out}=\bar{A} \qquad \ldots \quad (16.1)$$

The bar over A represents NOT. Hence if the letter A represents DOWN level (0), $\bar{A}$ represents UP (1) and if $A=1$, $\bar{A}=0$. Or in other words, $\bar{0}=1$, and $\bar{1}=0$.

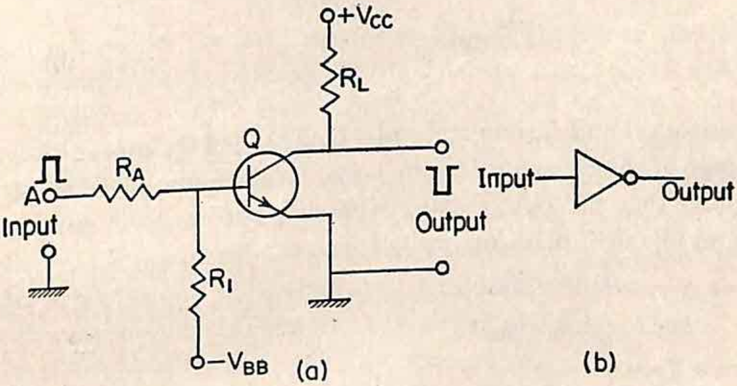


Fig. 16.8

Fig. 16.8 shows a NOT circuit and its symbolic representation. In the grounded emitter configuration in Fig. 16.8(a), the output is taken from the collector. When no signal is applied at the input, the transistor is cut off and the output is at V_{cc}, i.e., it is UP. On the other hand when a positive pulse is applied to the base, the transistor conducts and the collector voltage drops. Thus for a positive input, the output goes DOWN. We can therefore conclude that in a NOT circuit the output is present when an input is not applied. Similarly an output signal is not present when an input signal is applied.

16.6.6 NAND Gate and its Truth Table

The NAND gate is a combination of NOT and AND function. A two-input NAND gate and its symbolic representation is shown in

Fig. 16.9. In the absence of an input both Q_1 and Q_2 are forward-biased and conducting heavily. Thus when there is no signal on A or B the output voltage taken from collector to ground is close to zero. When a positive pulse appears on A but not on B, Q_1 cuts off but Q_2 still conducts and the output is still UP. Similarly if a positive pulse appears on B but not on A, the output is *UP*. But if positive pulses appear on A and B simultaneously, both Q_1 and Q_2 are cut off and the voltage at the collector drop to $-V_{cc}$. So the output is DOWN. Thus we find that the NAND gate is nothing but an AND gate with its output inverted, mathematically which can be expressed as,

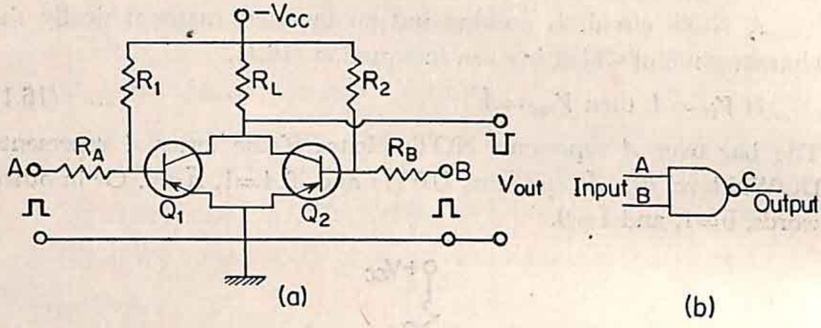


Fig. 16.9

$$\bar{A}+\bar{B}=V_{out}$$

or, $$\overline{A.B}=V_{out} \qquad \ldots \qquad (16.2)$$

TRUTH TABLE

All the possible conditions in a two-input NAND gate are given in Table 16.3.

TABLE 16.3: NAND Truth Table

Inputs		Output
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

16.6.7 NOR Gate and its Truth Table

The NOR gate is a combination of NOT and OR logic, the characteristic of which is that the output is produced without application of signal to input *A*, nor to input *B*, ……, nor to input *N*, nor to any combination of inputs. Fig. 16.10(a) is a NOR gate with two inputs while Fig. 16.10(b) is its logic symbol.

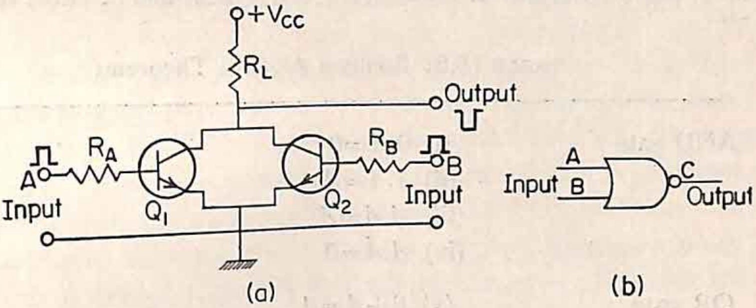


Fig. 16.10

Let us consider the basic circuits of Q_1 and Q_2. When the input signal is absent both the bases are returned to ground through the input circuits (not shown in the figure). So Q_1 and Q_2 are cut off for lack of forward bias. The output, common to both Q_1 and Q_2, taken from the collector resistor R_L is therefore equal to $+V_{cc}$ when no input signal is present on *A* or on *B*. If a positive pulse is applied at input *A* or *B* or both, Q_1 or Q_2 or both respectively conduct and a negative pulse appears at the output. The output is therefore DOWN. So we have an effect of an inverter (NOT) and an OR circuit in the operation of this gate, mathematically which can be expressed as,

$$\overline{A+B}=V_{out}$$

$$\text{or,}\quad \bar{A}.\bar{B}=V_{out} \qquad \ldots \qquad (16.3)$$

TRUTH TABLE

All the possible conditions in a two-input NOR gate are given in Table 16.4.

TABLE 16.4: NOR Truth Table

Inputs		Output
A	*B*	*Y*
0	0	1
0	1	0
1	0	0
1	1	0

16.6.8 Boolean Algebra

George Boole (1815–1864), an English mathematician, first developed the logical algebra greatly aided for the analysis of logical networks. A list of theorems in Boolean algebra is presented in Table 16.5.

TABLE 16.5: Boolean Algebra Theorems

AND gate	(i) $0.A=0$
	(ii) $1.A=A$
	(iii) $A.A=A$
	(iv) $A.\bar{A}=0$
OR gate	(v) $0+A=A$
	(vi) $1+A=1$
	(vii) $A+A=A$
	(viii) $A+\bar{A}=1$
NOT gate	(ix) $(\bar{A})=A$
Commutation	(x) $A+B=B+A$
	(xi) $A.B=B.A$
Association	(xii) $A+(B+C)=(A+B)+C$
	(xiii) $A.(B.C)=(A.B).C$
Distribution	(xiv) $A.(B+C)=A.B+A.C$
	(xv) $(A+B).(A+C)=A+B.C$
Absorption	(xvi) $A+A.B=A$
	(xvii) $A.(A+B)=A$
De Morgan's theorems	(xviii) $(\overline{A+B})=\bar{A}.\bar{B}$
	(xix) $A.B=\bar{A}+\bar{B}$

The equations above may be proved by considering the definitions, or truth tables or the behaviour of the circuits discussed earlier. In the table the De Morgan's theorems are interesting enough showing a useful relation between AND and OR functions.

The theorems of Boolean algebra are utilized to simplify digital logic networks in a similar way as the mathematical logic is utilized for manipulating ordinary algebraic expressions.

16.7 Binary Operation of a System

The binary system of arithmetic has only two possible states to represent all quantities. These two states are either 0 (zero) or 1 (one). Since 0 and 1 can be easily represented by two-state digital circuits, the binary operation finds wide use in computer technology. Thus a hole in a card can represent a binary 1 while no hole is a binary 0. Similarly the magnetic flux of a magnetic material can represent 1 in one direction and 0 in the opposite direction. In a computer, to transmit digits from one part to another, a binary 1 can be represented by a positive level and a binary 0 by a negative level or *vice versa*. Various designations are used, in general, for the two quantized states of a binary system, the most common of which are given in Table 16.6.

TABLE 16.6: Binary-state Terminology

	1	2	3	4	5	6	7
One state	True	Closed	High	Up	Off	Yes	1
Other state	False	Open	Low	Down	On	No	0

In logic a statement may be either true or false which is the notation under 1. Similarly a switch may be either closed or open as shown under notation 2 and so on.

A binary digit (either 0 or 1) is called a bit and a group of bits having a significance is called a code, word or byte.

16.7.1 Binary Numbers

For explaining the binary numbers, let us start with the familiar decimal system based on the use of 10 digits. Consider, as an example, the meaning of the decimal number 634 which can be written as follows:

$$\begin{aligned}634 &= (6\times10^2)+(3\times10^1)+(4\times10^0)\\ &= 600+30+4.\end{aligned}$$

It is seen therefore, that in a number the individual digits represent coefficients for the increasing powers of 10. The farthest digit to the right is the coefficient of the 0th power, the next is the coefficient of the 1st power and so on. In general, any decimal number can be represented by the equation

$$Y = d_n\times r^n + d_{n-1}\times r^{n-1} + \ldots + d_1\times r^1 + d_0\times r^0 \quad \ldots \quad (16.4)$$

where Y is the entire number, d_n is the nth digit from the point and r

is the radix or base. This equation can also be applied to the binary system as discussed below.

Since only two digits (0 and 1) are available in a binary system, the individual digits represent the coefficients of powers of 2 rather than 10 as in the decimal system. The binary number 10111, as an example, may be solved as follows:

$$\begin{aligned}Y&=d_4\times r^4+d_3\times r^3+d_2\times r^2+d_1\times r^1+d_0\times r^0\\&=1\times 2^4+0\times 2^3+1\times 2^2+1\times 2^1+1\times 2^0\\&=16+0+4+2+1=23\end{aligned}$$

or arithmetically we can write, $10111_2=23_{10}$.

This means the binary number 10111 represents the same quantity as the decimal number 23. A short list of decimal-binary equivalents is given in Table 16.7.

TABLE 16.7: Equivalent Numbers

Decimal notation	Binary notation
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010

16.7.2 Decimal to Binary Conversion

The order of a binary number is designated as 1, 2, 4, 8, 16, 32, 64, 128, 256, etc. and not as unit, tens, hundreds, thousands, etc. as in the decimal system. There are two methods for converting a decimal to a binary number.

In the first method a table of powers of 2 is utilized (Table 16.8). The decimal number to be evaluated is taken and the largest power of 2 from the table is noted without exceeding the original number. Then subtract the table-oriented number from the original number and repeat the process for the remainder until it becomes zero. Next, add the binary numbers obtained from the Table to get the answer.

TABLE 16.8: Power of 2

2^n	n
1	0
2	1
4	2
8	3
16	4
32	5
64	6
128	7
256	8
512	9
1024	10
...	...

In the second method of converting decimal to binary, the number is successively divided by 2 and its remainders recorded. The final binary result is obtained by reading the remainders from the bottom to the top.

16.7.3 Binary Addition

Addition of binary numbers is very simple. The addition of two binary numbers *A* and *B* can be done by using the Truth Table 16.9. The Table shows all the possible combinations of *A* and *B*.

TABLE 16.9: Truth Table for Addition

Inputs		Sum	Carry
A	*B*		
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

A digit, in the fourth entry of Table 16.9, is carried by shifting it to the next position to the left.

Binary numbers can also be subtracted, multiplied and divided using similar rules as applied for addition.

Examples

1. Convert 19_{10} to binary

1st method:

From Table 16.8, the largest number without exceeding 19 is 16	$16=10000$
$19-16=3$	
From the table, the largest number without exceeding 3 is 2	$2=\quad 10$
$3-2=1$	
1 is the largest number	$1=\quad 1$
Adding the binary numbers	$19=10011_2$

$\therefore\ 19_{10}=10011_2$

2nd method:

Successive division		Remainders
2	19	
2	9	1
2	4	1
2	2	0
2	1	0
	0	1

Reading the remainders from the bottom to the top, the result is

$$19_{10}=10011_2$$

2. Convert 200_{10} to binary

1st method:

$$\begin{array}{lr} 200-128=72 & 128=10000000 \\ 72-64=8 & 64=1000000 \\ & 8=1000 \\ \hline & 200=11001000_2 \end{array}$$

$$\therefore \quad 200_{10}=11001000_2$$

2nd method:

Successive division		Remainders
2	200	
2	100	0
2	50	0
2	25	0
2	12	1
2	6	0
2	3	0
2	1	1
	0	1

Reading the remainders from the bottom to the top

$$200_{10}=11001000_2$$

3. Add the binary numbers 0110 and 0101

The factors to be added are 0110 and 0101. By using Table 16.9 we get the following result:

Binary	*Decimal*
0110	6
0101	5
1011	11

4. Add the binary numbers 00101 and 00111

Binary	*Decimal*
00101	5
00111	7
01100	12

5. Subtract the binary 00111 from the binary 01100

Binary	*Decimal*
01100	12
00111	7
00101	5

6. Subtract the binary 00001 from the binary 00010

Binary	*Decimal*
00010	2
00001	1
00001	1

Self-Test

Read each of the following and provide the appropriate words.

(a) An integrated circuit is a complete circuit etched into a — chip.

(b) The active elements in an IC are — and —.

(c) The passive elements in an IC are — and —.

(d) An IC is a complete circuit consisting of discrete components. (True/False)

(e) ICs may be broadly classified as — and — devices.

(f) ICs usually come in one of the three different cases. These are: (a) —, (b) — and (c) —.

(g) An audio amplifier is an example of — IC.

(h) Digital ICs are found in — — etc.

(i) Digital circuits are linear circuits. (True/False)

(j) Logic gates used in computers are contained in —.

(k) In a three-input AND circuit all the inputs must be — for the output to be UP.

(l) In a two-input AND circuit if the output is —, then either or both the inputs must be DOWN.

(m) In a four-input OR circuit at least — input(s) must be — for the output to be UP..

(n) The expression $A.B=C$ is the characteristic of a — input gate.

(o) The symbol '+' when used in logic equations stands for —.

(p) The equation $A+B=C$ represents the characteristic of a — input — gate.

(q) In a NOT circuit the output is — when an input is not applied.

(r) The — gate is a combination of NOT and AND function.

(s) A NAND gate is nothing but the — gate with its inverted output.

(t) We have an effect of an inverter and an OR circuit in the operation of — gate.

(u) A number expressed in binary form has one and only one equivalent decimal value. (True/False)

(v) The number 14 written in the binary form is —.

(w) The number 20 written in the binary form is —.

(x) The value of the number 1011 in decimal form is —.

(y) The value of the number 11011 in decimal form is —.

(z) The result of adding the following binary numbers is

$$\begin{array}{r} 1011011 \\ 1101001 \\ \hline \\ \hline \end{array}$$

Review Questions

1. Describe briefly the principle and the fabrication processes of an integrated circuit.

2. What are the four advantages of an intergrated circuit?

3. How are the integrated circuits broadly classified?

4. What is a logic circuit? Define (a) positive logic and (b) negative logic.

5. Identify the two states of a logic circuit.

6. From the Table given below what conclusions can you draw about the characteristics of an AND circuit?

TABLE 16.10: AND Logic

Inputs		Output
A	*B*	*Y*
0	0	0
0	1	0
1	0	0
1	1	1

7. Complete the following Table for the OR circuit

TABLE 16.11: OR Logic

Inputs		Output
A	*B*	*Y*
0	0	
0	1	
1	0	
1	1	

8. Define an AND gate and give its truth table.

9. Explain with circuit diagram the operation of an AND gate.

10. Define an OR gate and explain its operation.

11. Show how to implement an AND with OR gate.

12. What are the characteristics of an inverter?

13. Define a NOT gate and give its truth table.

14. What are the characteristics of (a) NOR and (b) NAND gates? Explain their operations.

15. What is meant by binary operation of a system?

16. What are binary numbers. Explain with illustration how a decimal number can be converted to a binary number?

17. Give the truth table for binary addition.

18. Why is the binary system preferred to the decimal system for use in computers?

19. Write the quantity 196 in binary form. (*Ans.* 11000100)

20. Convert the binary quantity 1101001 in decimal form. (*Ans.* 105)

21. Add the binary numbers 10001 and 01111. (*Ans.* 100000)

22. Add the binary numbers 00010 and 00010. (*Ans.* 00100)

CHAPTER 17

OPERATIONAL AMPLIFIER

17.1 Introduction

An operational amplifier, often referred to as OP AMP, is a high gain, direct-coupled amplifier whose response characteristics are controlled externally by negative feedback arrangement. Now-a-days OP AMPs are widely used in various branches of electronics particularly in linear and digital circuits. OP AMPs are suitably used in computer technology to perform mathematical operations like summing, differentiation and integration. These are also used as video and audio amplifiers, oscillators, etc.

17.2 Symbol

The symbol for an operational amplifier is shown in Fig. 17.1. The figure shows that the amplifier has two inputs of which one is marked plus (+) and the other is marked minus (−). The plus input is the noninverting input while the minus input is the inverting input. A signal applied to the plus input will be appeared in the same phase at the output. On the other hand, a signal applied to the minus input will be shifted in phase 180° at the output. Since the internal circuit of an OP AMP is very complicated, the symbol shown above is used in different circuit diagrams.

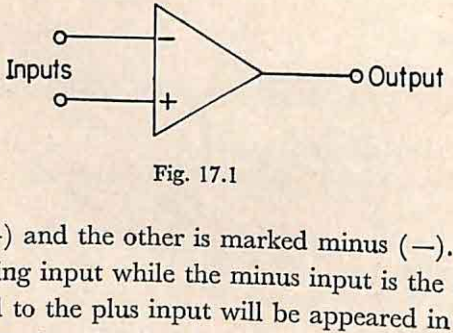


Fig. 17.1

17.3 Specifications of OP AMP

With each operational amplifier the manufacturers supply a basic diagram, a circuit diagram and other specifications including performance graph. As an example a basing diagram of the 741C OP AMP showing all terminal connections is shown in Fig. 17.2(a) and its circuit diagram is shown in Fig. 17.2(b). The OP AMPs are available in different packages which can be divided into two grades—the military (M) and commercial (C). The commercial grade of 741 HC has the following maximum ratings.

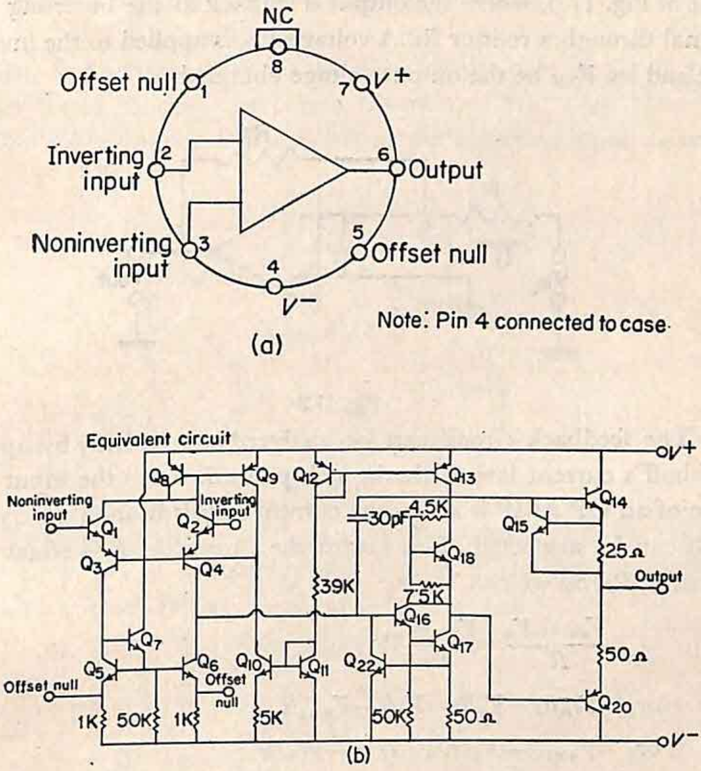


Fig. 17.2

Supply voltage ± 18 V
Differential input voltage ± 30 V
Internal power dissipation 500 mW
Operating temperature 0 to 70°C.

17.4 Characteristics of an OP AMP

An ideal operational amplifier has the following important characteristics which do not drift with temperature:

(i) Input resistance$=\infty$
(ii) Output resistance$=0$
(iii) Bandwidth$=\infty$
(iv) Voltage gain$=-\infty$
(v) $V_{out}=0$ when $V_1=V_2$ independent of the magnitude of V_1.

17.5 Operational Feedback

To explain the features of an OP AMP, let us consider the basic circuit of Fig. 17.3, where the output is fedback to the inverting input terminal through a resistor R_f. A voltage V_{in} is applied to the inverting input and let V_{out} be the output voltage obtained.

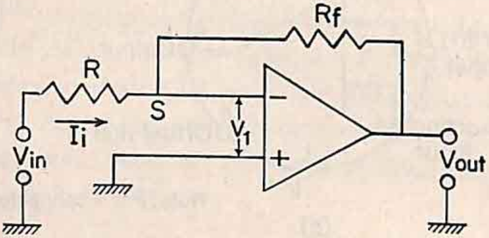


Fig. 17.3

The feedback circuit can be analyzed conveniently by applying Kirchhoff's current law to the branch point S. Since the input impedance of an OP AMP is large, the current in this branch is very small which can be neglected. This means the current in R is equal to the current in R_f. So we can write,

$$\frac{V_{in}-V_1}{R}=\frac{V_1-V_{out}}{R_f} \quad \cdots \quad (17.1)$$

or, $V_{in}R_f-V_1R_f=V_1R-V_{out}R$

or, $V_{out}R-V_1(R+R_f)=-V_{in}R_f$

Putting $V_1=-\frac{V_{out}}{A}$ … (17.2)

where A=gain of the amplifier

We have,

$$V_{out}R+\frac{V_{out}}{A}(R+R_f)=-V_{in}R_f$$

or, $V_{out}R\left[1+\frac{1}{A}+\frac{R_f}{AR}\right]=-V_{in}R_f$

or, $V_{out}\left[1+\frac{1}{A}+\frac{R_f}{AR}\right]=-\frac{R_f}{R}V_{in}$

Since the gain of the OP AMP is very large we have,

$$V_{out}=-\frac{R_f}{R}V_{in} \quad \cdots \quad (17.3)$$

Equation (17.3) shows that the output voltage is the product of the input signal and the constant factor $(-R_f/R)$. The negative sign indicates that the sign of the output is inverted in comparison to the input. The expression for the gain of this amplifier is,

$$\text{Gain}=R_f/R \qquad \dots \qquad (17.4)$$

Next, to find an expression for V_{out} for the case of noninverting amplifier let us consider the circuit diagram of Fig. 17.4. Note that here also the resistance R is applied to the inverting input as before

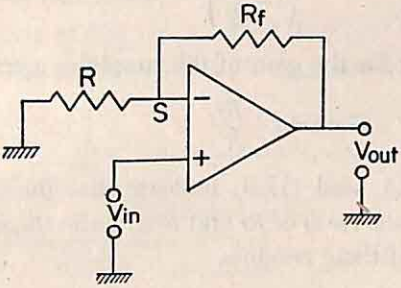


Fig. 17.4

but the voltage is applied to the noninverting input. Let at the point S, i.e., at the inverting terminal the voltage is V_2 so that by applying Kirchhoff's current law at S we get,

$$\frac{V_2}{R}=\frac{V_{out}-V_2}{R_f} \qquad \dots \qquad (17.5)$$

or, $$V_2R_f=V_{out}R-V_2R$$

or, $$V_2(R+R_f)=V_{out}R \qquad \dots \qquad (17.6)$$

Again if A is the voltage gain of the OP AMP then,

$$A=\frac{V_{out}}{V_{in}-V_2}$$

or, $$AV_{in}-AV_2=V_{out}$$

or, $$V_2=V_{in}-\frac{V_{out}}{A} \qquad \dots \qquad (17.7)$$

Substituting the value of V_2 from equation (17.7) in equation (17.6) we get,

$$\left(V_{in}-\frac{V_{out}}{A}\right)(R+R_f)=V_{out}\,R$$

or, $$V_{in}\,(R+R_f)=V_{out}\,R+\frac{V_{out}\,R}{A}+\frac{V_{out}\,R_f}{A}$$

$$=V_{out}\,R\left[1+\frac{1}{A}+\frac{R_f}{AR}\right]$$

Since A is very large, we have,

$$V_{out}\, R = V_{in}\,(R+R_f)$$

$$\text{or,}\quad V_{out} = V_{in}\left(1+\frac{R_f}{R}\right) \qquad \ldots \qquad (17.8)$$

Equation (17.8) shows that the output voltage of a noninverting amplifier is the product of the input signal and the constant factor $\left(1+\frac{R_f}{R}\right)$.

The expression for the gain of this amplifier gives,

$$\text{Gain} = 1+\frac{R_f}{R} \qquad \ldots \qquad (17.9)$$

Equations (17.3) and (17.8) indicate that the output voltage is dependent only on the ratio of R_f and R and also the gain is dependent only on the value of these resistors.

17.5.1 Virtual Ground

The point S in the operational amplifier is very significant which may be explained by considering the effective impedance between S and ground. If I_i be the input current then the impedance Z_s is given by,

$$\begin{aligned} Z_s &= \frac{V_1}{I_i} \\ &= \frac{V_1}{\dfrac{V_1-V_{out}}{R_f}} \left(\because \; I_i = \frac{V_1-V_{out}}{R_f}\right) \\ &= \frac{V_1 R_f}{V_1-V_{out}} \\ &= \frac{R_f}{1-\dfrac{V_{out}}{V_1}} \\ &= \frac{R_f}{1+A}\left(\because \; A = -\frac{V_{out}}{V_1}\right) \qquad \ldots \qquad (17.10) \end{aligned}$$

Equation (17.10) indicates that for a large gain of the amplifier, the impedance between the branch point S to ground is very low. For example, if $A=10^4$ and $R_f=10^5$ ohms then $Z_s=10$ ohms only. Such a low impedance is due to the negative feedback voltage of the OP AMP which cancels the input signal at S. In this way by feedback action the point S tends to keep at ground potential and hence it is called a virtual ground.

17.6 Applications

An operational amplifier, as the name implies, can be used to perform many mathematical operations. Some of these applications are discussed below.

17.6.1 Adder (or Summer)

In the circuit of Fig. 17.5, the OP AMP is used to obtain an output by a linear combination of a number of input signals to the branch point S. Since a virtual ground exists at the OP AMP input, in this circuit the sum of the currents in R_1 and R_2 becomes equal to the current in R_f.

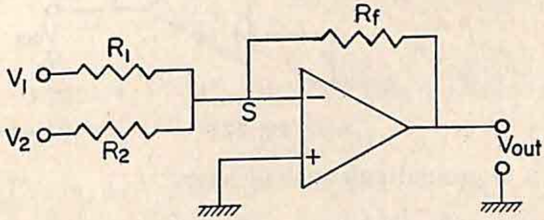


Fig. 17.5

i.e., $$\frac{V_1}{R_1}+\frac{V_2}{R_2}=-\frac{V_{out}}{R_f}$$

or, $$V_{out}=-R_f\left(\frac{V_1}{R_1}+\frac{V_2}{R_2}\right) \quad \dots \quad (17.11)$$

When $R_1=R_2$,

$$V_{out}=-\frac{R_f}{R_1}(V_1+V_2) \quad \dots \quad (17.12)$$

That is the output voltage is proportional to the sum of the inputs. Again it is seen that if, $R_1=R_2=R_f$ then,

$$V_{out}=-(V_1+V_2) \quad \dots \quad (17.13)$$

This means the output voltage is the sum of the input voltages with an inverted sign.

The summer of Fig. 17.5 can easily be modified by a large number of inputs by connecting one resistor for each additional input. Because of the virtual ground, there is a minimum of interaction between the individual signal sources. The point S where the addition takes place is called the summing point.

17.6.2 Integrator

If the feedback resistor R_f is replaced by a capacitor C, as shown in Fig. 17.6, the circuit becomes an integrator, i.e., it performs the mathematical operation of integration.

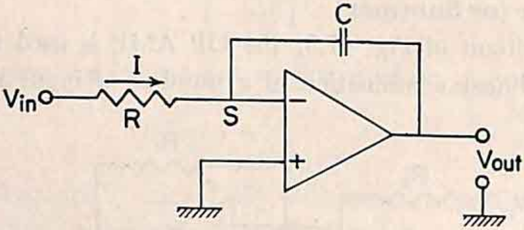


Fig. 17.6

Since S is at ground potential we have,

$$V_{out}=\frac{q}{C}=\frac{1}{C}\int_0^t I\,dt$$

Since, $I=-\dfrac{V_{in}}{R}$ we get,

$$V_{out}=-\frac{1}{CR}\int_0^t V_{in}\,dt \qquad \dots \qquad (17.14)$$

The output voltage of the amplifier thus becomes proportional to the integral of the imput signal. The integral of the sum of several signals may be obtained by using several input resistors.

17.6.3 Differentiator

If the resistor R and the capacitor C are interchanged, as shown in Fig. 17.7, the circuit becomes a differentiator which gives the time derivatives of the input signal.

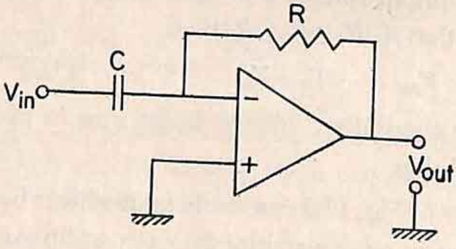


Fig. 17.7

At the summing point we have,

$$I=\frac{dq}{dt}=\frac{d}{dt}(C\,V_{in})$$

$$=C\frac{dV_{in}}{dt} \qquad \ldots \qquad (17.15)$$

Again since $I=-\frac{V_{out}}{R}$, we have, by equating

$$-\frac{V_{out}}{R}=C\frac{dV_{in}}{dt}$$

$$\text{or,}\quad V_{out}=-CR\frac{dV_{in}}{dt} \qquad \ldots \qquad (17.16)$$

Thus the output is proportional to the time derivative of the input. If we put the input signal $V_{in}=\sin\omega t$, we get,

$$V_{out}=-CR\,\frac{d}{dt}(\sin\omega t)=-CR\omega\cos\omega t \qquad \ldots \qquad (17.17)$$

Equation (17.17) suggests that the magnitude of the output voltage increases linearly with increasing frequency and hence the differentiator has high gain at higher frequencies.

17.7 Differential Amplifier

The differential amplifier, abbreviated as DIFF AMP, is the basic stage of an integrated OP AMP with differential input. Its design is therefore mainly related to IC fabrication techniques. However, employing discrete components it is also used in some circuits.

Generally the function of a differential amplifier is to amplify the difference of two signals. Fig. 17.8(a) shows a linear active device with two input signals V_1, V_2 and one output signal V_{out}, all measured with respect to ground. Fig. 17.8(b) represents the basic differential amplifier circuit, the two transistors, Q_1 and Q_2, of which have identical characteristics with a common emitter resistor R_E. The collector load

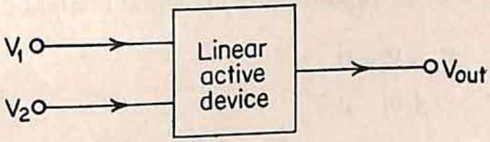


Fig. 17.8(a)

resistors are also made equal, i.e., $R_{L1}=R_{L2}$ and the inputs are identical, i.e. $R_1=R_2$ and $V_1=V_2$.

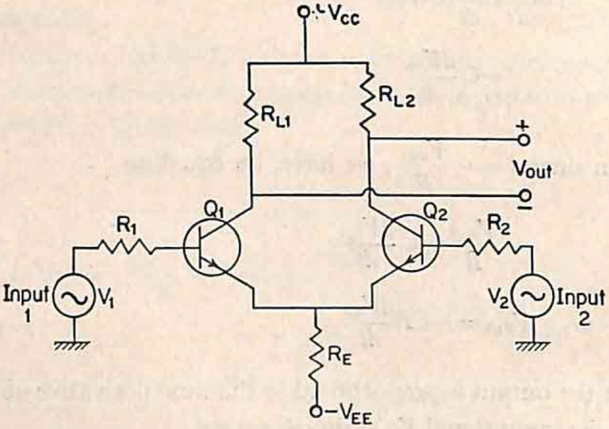


Fig. 17.8 (b)

In an ideal differential amplifier the output signal is proportional to the difference between the two input signals. This can be expressed as,

$$\begin{aligned} V_{out} &= A(V_1-V_2) \\ &= AV_d \qquad \cdots \qquad (17.18) \end{aligned}$$

where, $V_d=V_1-V_2$

and $A=$ the gain of each transistor.

Equation (17.18), as stated, is for an ideal case. For a practical DIFF AMP equation (17.18) is not considered, in general, as the output depends not only upon the difference signal V_d but also on the average level, known as the common mode signal. This common mode signal can be represented by V_c where,

$$V_c \equiv \tfrac{1}{2}(V_1+V_2) \qquad \cdots \qquad (17.19)$$

(i) When the two input signals are equal in amplitude and phase, we have,,

$$V_1-V_2=0$$

$$V_{out}=A(0)=0 \qquad \cdots \qquad (17.20)$$

(ii) When the two input signals are equal in amplitude but 180° out of phase, we have,

$$V_1=-V_2, \text{ or, } V_2=-V_1$$

and then, $V_{out}=A[V_1-(-V_1)]=2AV_1$ ... (17.21)

Therefore in such differential amplifier the output signal becomes twice the gain times the input signal.

Self-Test

Read each of the following and provide the appropriate words:

(a) A signal applied to the plus input of an OP AMP will be shifted in phase 180° at the output. (True/False)

(b) OP AMPs are available in different packages which can be divided into two grades, (i) military and (ii) —.

(c) The output resistance of an ideal OP AMP is —.

(d) The gain of a noninverting amplifier is —.

(e) For a large gain of the amplifier, the impedance between the branch point S to ground is very —.

(f) If the feedback resistor is replaced by a —, the circuit becomes an integrator.

(g) The function of a differential amplifier is to amplify the — of two signals.

Review Questions

1. Write down the characteristics of an ideal OP AMP.

2. Explain the theory of an OP AMP when the signal is applied to the (a) inverting input and (b) noninverting input separately.

3. What is meant by 'virtual ground' of an OP AMP?

4. Clearly explain with circuit diagrams the principle of (a) an adder, (b) integrator and (c) differentiator.

5. Define an ideal DIFF AMP. Discuss its theory with suitable circuit diagram.

APPENDIX A

DEFINITIONS, CHARTS, TABLES AND SUNDRY DATA

1. **Definitions**

Most of the words have already been defined or explained in the earlier chapters with a reference in the index. Some additional definitions are given here.

A-battery: Battery for supplying power to the filaments. This is also known as L. T. battery.

Absolute value: Refers to magnitude without direction. It is designated as $|A|$.

A.C./D.C. receiver: Receiver which operates from either power source.

Air-core: Without iron in its magnetic circuit.

Alternating voltage (or current): Which alternates its direction regularly with an average value of zero.

Amplification: Increase of signal voltage or power.

Anode: Positive electrode or plate.

Attenuation: Decrease of the signal voltage or power.

Audio frequency: Frequency audible to the normal human ear.

Axial leads: Leads from the ends of capacitors, resistors, etc.

B-battery: Battery for supplying power to the plate and screen circuits. This is also known as H.T. battery.

B-supply: Plate and screen voltage source for an amplifier or a receiver.

Band: Frequencies between a fixed lower and upper limit.

Band-pass: Passing only a specific band of frequencies.

Bass: Low audio frequencies.

Beating: A periodic variation in the amplitude of an oscillation (or sound) resulting from two or more oscillations of different frequencies.

Bias: Application of a voltage to the grid to get the required operating point.

Bleeder resistor: Resistor used across a voltage source as an additional load in order to provide a good regulation.

Blocking: Cutting off the plate current by a high negative bias on the grid.

By-pass condenser: Allows alternating current to by-pass part of a circuit.

C-battery: Battery for supplying voltage to the grid. This is also known as bias battery.

Carrier wave: Unmodulated wave radiated by a broadcast station.

Cascade: In an amplifier circuit if the output of one valve is applied to control the grid circuit of another valve then the valves are said to be in cascade.

Cathode: Negative electrode.

Cathode current: Total electronic current passing through the cathode.

Choke coil: Inductance.

Co-axial: Having a common axis.

Converter: It is that stage of a receiver which converts radio frequency to intermediate frequency.

Co-planar: Same plane.

Core: Centre of a coil.

Cross modulation: Modulation of the carrier of the desired signal by an undesired signal.

Cut-off frequency: Frequency beyond which attenuation increases rapidly.

Demodulation: A process by which the carrier frequency is removed and the modulating frequencies retained.

Dissipation: Loss of electrical energy.

Drain: To take current from a voltage source.

Efficiency: Percentage of output to input.

Electromotive force: It is that force which tends to cause an electric current to flow in a circuit.

Envelope: It is obtained by passing one smooth curve through the maximum, another through the minimum points or peaks of the wave.

Equivalent circuit: A comparatively simple circuit which may be used in calculations, having the same effect as in actual circuit.

Excitation: Signal voltage applied to the control electrode of the valve.

First detector: Same as converter.

Frequency: Reciprocal of the time period; the number of cycles per second.

Frequency changer: Same as converter.

Fundamental frequency: Lowest frequency of a number of harmonically related frequencies.

Generator: It develops either direct or alternating electrical voltage at any frequency.

Gramophone: Also known as phonograph.

Ground: Conductor serving as the earth.

Harmonic frequency: The frequency which is the multiple of fundamental frequency. Twice the fundamental frequency is called the second harmonics and so on.

Hertz: Cycles per second.

High level: A relative term indicating the final level of an amplifier.

High-pass filter: A filter which passes all the frequencies above a critical value.

Honeycomb winding: A coil winding in which spaces are left between turns so as to give the appearance of a honeycomb.

Intensity: The strength of a quantity like pressure, voltage or current.

Intermediate frequency: A frequency to which the incoming signal is altered in superheterodyne receiver.

Layer winding: A coil winding in which one layer is wound over the other.

Lead: Connecting wire.

Line voltage: Mains voltage, i.e., the voltage of the power lines.

Litz wire: A conductor composed of a number of fine, separately insulated strands.

Load: A device which absorbs electrical power.

Low level: A relative term indicating the level of the early stages of an amplifier.

Low-pass filter: A filter which passes all frequencies below a critical value.

Lower sideband: The sideband containing all the frequencies below the carrier frequency which has been amplitude modulated.

Manual: Adjusted by hand.

Memory: In computers or recording instruments any device in which information is introduced and later extracted.

Metal-film resistor: A resistor constructed by coating a high-temperature insulator, such as quartz, ceramic or mica with a metal film by evaporation or firing.

Mev: Abbreviation for million electron volt.

Mho: Reciprocal of ohm. It is the unit of conductance or admittance.

Microfarad: One millionth of a farad.

Microphone: An electro-acoustic transducer which responds to sound waves and delivers equivalent electrical waves.

Monitoring amplifier: An amplifier designed to amplify signals with the minimum distortion. It is used in audio engineering to check programme performance or the level of recording signals.

Motorboating: At low audio frequency amplifiers, self-oscillation resulting in a noise like those of a motor boat.

Mutual inductor: Inductor used to change the mutual inductance between two circuits.

Negative bias: Voltage applied to the control grid of a valve to make it negative with respect to cathode.

Negative electrode: The cathode of a valve.

Negative glow: In a discharge tube the luminous glow between cathode dark-space and Faraday dark-space.

Negatron: Negative electron.

Neon: An inert gaseous element with atomic No. 10. It has a characteristic red glow when ionized. In electronics neon tubes are extensively used as an indicator and also in voltage regulator.

Neon oscillator: Oscillator based on neon lamp and a capacitor with some times a resistor in the circuit.

Network: An electrical circuit. A system of interconnected admittances.

Network analyser (calculator): An assembly of circuit elements so as to form models of electrical networks. These are widely used to solve problems in power distribution systems.

Node: A point on a stationary wave which has zero amplitude.

Noise: Undesired electrical disturbance within the useful frequency band.

Noise field intensity: Measurement of field intensity of electromagnetic waves.

Noise level: Value of noise integrated over a specified frequency range. It is expressed in decibels relative to a standard level.

Nonlinear: Distorted.

On-off control: A control system of only two choices.

Open circuit: A circuit in which continuity is incomplete and therefore carry no current.

Open grid: Floating grid.

Oscillation: Any quantity is in a state of oscillation when the value of that quantity changes continually between maximum and minimum values.

Output stage: The voltage, current or power delivered by a circuit at the final stage.

Parallel circuit: A circuit in which components are in parallel so that the current divides between them.

Parallel digital computer: A digital computer where the digits are handled in parallel.

Paschen's law: The p.d. which initiates discharge in a gas is the product of the electrode separation and gas pressure.

Phon: Unit of loudness level of sound.

Photocurrent: An electric current which varies with illumination.

Potential: The potential at a point is the p.d. between that point and earth.

Pulse: Variation of a quantity whose value is normally constant. The characteristics of a pulse are a rise, a finite duration and a decay.

Q factor: The ratio of reactance to resistance of a coil, condenser or resonant circuit.

Quiescent current: The current flowing to or from an electrode under specified normal conditions when the signal is absent to the input electrode.

RADAR: Abbreviation of radio detection and ranging.

Radial lead: A lead at 90° to the axis.

RF: Abbreviation of radio frequency. It is a frequency at which electromagnetic radiation is used for telecommunication.

Root-mean square (r.m.s.) value: The square root of the mean (average) value of the squares of the instantaneous values taken over a complete cycle.

Secondary battery: A battery made up of storage cells.

Secondary emission: Ejection of electrons due to the impact of charged particles.

Self-bias: Bias developed due to the flow of valve current through a resistor in the cathode circuit or through a grid resistor in the grid circuit and not by battery.

Sensitivity of radio receiver: Minimum input signal required to produce a specified output signal having a specified signal-to-noise ratio.

Short circuit: An accidental low resistance connection across part of a circuit causing an excessive current flow.

Sideband: A band of frequencies within which lie all the frequencies of the waves produced by modulation.

Signal: An electrical quantity which gives information by varying in some manner.

Sinusoidal: The form of a sine wave.

Space current: Cathode current.

Symmetrical: Having same characteristics for conduction in both the directions.

Tap: Connecting point other than the end.

Terminal: Point to which connections are made.

Tolerance: Maximum permissible variation from an assigned value.

Toroidal coil: A coil wound in the form of a toroidal helix.

Transducer: An electrical transducer is an electrical network by which energy may flow from one transmission system to the other.

Treble: High audio frequencies.

Tuner: A device for tuning.

Two-way communication: Communication between radio stations having both transmitting and receiving equipments.

Unidirection current: Current which may change its value but never reverses its direction.

Voice coil: Moving coil of a dynamic loudspeaker.

Voltage regulator: An electronic device which regulates the voltage across a load.

VTVM: Abbreviation for vacuum-tube valve voltmeter.

Whistling atmospherics: Audio frequency noises due to electrical reverberation in the ionosphere.

Work function (thermoionic): The thermoionic energy required to eject an electron from a hot metal.

X-band: Radar frequencies from 5,200 to 10,900 MHz.

Yagi aerial: An aerial array which is prototype of most television receiving aerial.

Y-signal: The monochromatic signal in colour TV which conveys the intelligence of brightness or of luminance.

Zero signal: Having no signal input voltage.

2. Standard Frequencies

(a) Standard frequency ranges—The final acts of the International Telecommunication & Radio Conferences in 1947 proposed the following nomenclature of frequencies. Frequencies are expressed in kilocycles per second (kHz) at and below 30,000 kHz and in megacycles per second (MHz) above that frequency.

(b) Standard intermediate frequencies—It is recommended that the superheterodyne receivers operating in the MF band use an intermediate frequency of 455 kHz. This frequency is reserved in most countries of the world.

TABLE A.1: Standard Frequency Ranges

Frequency subdivision	Frequency range	Metric subdivision
Very Low Frequency (VLF)	below 30 kHz	myriametric waves
Low Frequency (LF)	30 to 300 kHz	kilometric waves
Medium Frequency (MF)	300 to 3000 kHz	hectometric waves
High Frequency (HF)	3000 to 30,000 kHz	decametric waves
Very High Frequency (VHF)	30,000 kHz to 300 MHz	metric waves
Ultra High Frequency (UHF)	300 to 3000 MHz	decimetric waves
Super High Frequency (SHF)	3000 to 30,000 MHz	centimetric waves
Extremely High Frequency (EHF)	30,000 to 30,0000 MHz	millimetric waves

The European "Copenhagen Frequency Allocations" provide the intermediate frequency in two ranges, viz., 415-490 kHz and 510-525 kHz. An intermediate frequency of 175 kHz is also used sometimes.

The American RTMA has standardized the following intermediate frequencies: (i) Standard broadcast receivers—either 260 or 455 kHz, (ii) VHF broadcast receivers—10.7 MHz.

3. Colour Codes

In fixed composition resistor with axial leads the value of the resistance is indicated by bands of colour around its body.

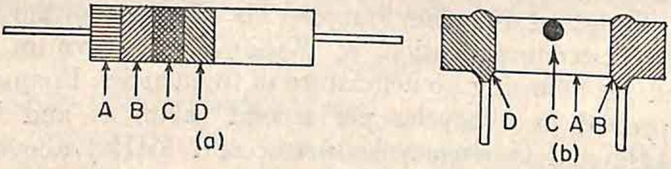


Fig. A. 1

Such a resistor is shown in Fig. A.1(a), where,

Band A is for the first significant figure,

Band B is for the second significant figure, Band C is for the decimal multiplier,

Band D, if any, is for the tolerance limits about the nominal resistance value.

TABLE A.2: Colour Codes

Colour	Significant figure	Decimal multiplier	Tolerance %
Black	0	1	
Brown	1	10	
Red	2	10^2	
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Grey	8	10^8	
White	9	10^9	
Gold	...	10^{-1}	± 5
Silver	...	10^{-2}	± 10
No colour	...	...	± 20

For resistors with radial leads the resistance values may be obtained in the same way as those for the axial leads. But sometimes these may also be colour coded as shown in Fig. A.1(b), where,

Body A corresponds to Band A above,

End B corresponds to Band B above,

Dot C (or Band C) corresponds to Band C above,

Band D corresponds to Band D above.

APPENDIX B

GLOSSARY OF INTEGRATED CIRCUIT TERMINOLOGY†

AC COUPLED FLIP-FLOP: An edge-triggered flip-flop that changes state due to the rise or fall of a clock pulse. It is characterized by having a maximum allowable rise or fall time.

ACCUMULATOR: A register for doing such arithmetic and logic functions as addition and shifting.

ACTIVE ELEMENTS: Those components in a circuit which have gain, or direct current flow, such as SCRs, transistors, thyristors, or tunnel diodes. They change the basic character of an applied electrical signal by rectification, amplification, switching, etc. (Passive elements have no gain characteristics. Examples: inductors, capacitors, resistors.)

ACTIVE PULL-UP: Similar to a pullup resistor, except a transistor replaces the resistor connected to the positive supply voltage. This allows low output impedance without high power consumption.

A-D: Analog-to-digital.

A-D ENCODER: Analog-to-digital encoder for changing an analog quantity to equivalent digital representation.

ADDER: A switching circuit which combines bits to generate their sum and carry.

ADDRESS: (*Noun*) A code label that identifies a specific location in a computer's memory where certain information is stored. (*Verb*) Selection of stored information for retrieval from a computer's memory.

AMBIENT TEMPERATURE: The environmental temperature in which a device operates, e.g., perhaps +150°C in a rocket, or −45°C in a remote Arctic weather station.

AMPLIFIER: A circuit used to increase the power, voltage, and/or current level of a signal.

AND (GATE): If and only if all inputs are true, the output is true.

ARITHMETIC UNIT: The part of a computer that performs arithmetic operations.

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† After Motorola Semiconductor Products, Inc.; edited in November, 1970.

ASTABLE: Refers to a device which has two temporary states. The device oscillates between the two states with a period and duty cycle predetermined by time constants. (*See* bistable.)

ASYNCHRONOUS: Nonclocked operation of a switching or logic network wherein the completion of one instruction or operation triggers the next.

ASYNCHRONOUS INPUTS: The terminals in a flip-flop which affect the output state of the flip-flop independently of the clock. Called set, preset, reset, or clear. Sometimes these are referred to as dc inputs.

BAR: A symbolization of the inverse or complement of a logic function. (*See* Q and $\overline{Q}$—read as Q-bar.)

BCD: Binary-coded decimal.

BINARY: A numbering system using only two symbols: 0 and 1.

BINARY-CODED DECIMAL (BCD) representation: A system of representing decimal numbers. Each decimal digit is represented by a combination of four binary digits (bits).

BINARY COUNTER: Flip-flops connected in cascade to perform binary counting. Four flip-flops have a counting capacity of 2^4, or 16: five cascaded flip-flops have a capacity of 2^5, or 32, etc. (Also called *binary scaler.*) (*Also see* counter *and* ring counter.)

BINARY LOGIC: Digital logic elements operating with two distinct states called true and false or high and low or on and off or 1 or 0. In computers the two states are represented by two different voltage levels.

BINARY-TO-1-OF-8 LINE DECODER: This digital function takes three input lines with eight possible states and decodes them internally, enabling only the one output line which corresponds to that particular combination of the three inputs.

BI-QUINARY COUNTER: A 4-bit counter capable of divide-by-two, divide-by-five, or divide-by-10 functions.

BISTABLE: A logic device that has two stable states. The flip-flop is an example of the bistable element. (A device with two temporary states is an astable device.) The flip-flop can be caused to go to either of the two states by input signals, but remains in that state after the input signals are removed. (*See* astable.)

BIT: An acronym for binary digit. In the binary numbering system, each of the two marks 0 and 1 is called a binary digit, or bit. The decimal number 39, converted to a binary number, becomes 100111 and is made up of six 0 or 1 marks, or six bits. A bit is the smallest divisible amount of information that can be stored in a flip-flop.

BLOCK DIAGRAM: A geometric drawing of the basic units in a circuit, interconnected by straight lines indicating current flow, signal flow, etc.

BOOLEAN ALGEBRA: A logical calculus, named for mathematician George Boole, using alphabetic symbols to stand for logical variables and 0 and 1 to represent states. (AND, OR, and NOT are the three basic logic operations in this algebra. NAND and NOR are combinations of the three basic operations.)

BUFFER: A digital circuit element used to increase fanout (the number of outputs a circuit can drive) or to convert input or output levels for signal-level compatibility. Also, any isolating amplifier stage.

BUS (LINE): A connection line for distribution of signals, power supply, or ground.

CASCADABLE COUNTER: A logic counting block that has the necessary connections available to allow the operation of more than one counter in series thus increasing the modulus of the counter sybsystem. (*See* cascading.)

CASCADING: Placing of two or more circuits in series, the output of one being connected to the input of the next in the series.

CENTRAL PROCESSING UNIT (CPU): The arithmetic and control portions of a computer.

CHIP: A tiny piece of semiconductor material scribed or etched from a semiconductor slice on which one or more electronic components are formed. (Also called *die.*)

CLEAR: To return a memory or storage element to its "standard" state, usually 0. Also called reset.

CLOCK: A pulse generator or signal waveform which synchronizes the timing of switching circuits and memory in a digital computer system. It determines the speed of the CPU.

CLOCKED: A term that refers to gating that is added to a basic flip-flop. This gating permits the flip-flop to change state only when a change in the clocking input or an enable level of the clocking input happens to be present.

CLOCK INPUT: That terminal on a flip-flop whose condition or change of condition controls the admission of data into a flip-flop through the synchronous inputs and thereby controls the output state of the flip-flop. The clock signal performs two functions: (1) it permits data signals to enter the flip-flop; (2) after entry, it directs the flip-flop to change state accordingly.

CLOCK RATE: The speed (frequency) at which the major portion of a computer or logic element operates, determined by the rate at which words or bits are transferred from one internal element to another. Clock rate is expressed in megahertz (if a parallel-operation machine: words; if a serial operation machine: bits).

CML: Current-mode logic, in which transistors operate in the unsaturated mode. This logic has ultra-fast switching speeds and low logic swings. (Also called ECL or MECL.*)

CMOS(COMPLEMENTARY MOS): With extra diffusions, a circuit with both *P*- and *N*-channel FETs on the same MOS wafer. CMOS, complementary metal-oxide-semiconductor logic, is designed to have extremely low power dissipation (essentially zero during stand-by) making it especially useful for remote applications where power is expensive. Other attributes: high noise immunity, high fanout, full power-supply logic swings, and ready acceptance of a wide range of power supplies.

COMPARATOR (DIGITAL): Used to check to see if both input words are identical, in which case EXCLUSIVE-NOR or coincidence gates can be used. Additional logic may also be added to indicate if one word is greater than or less than the other.

COMPARATOR (LINEAR *or* ANALOG): A device that compares an input voltage with a reference level. The output may indicate greater than, less than, or even equal to.

COUNTER: (1) A device capable of changing states in a specified sequence upon receiving appropriate input signals. (2) A circuit which provides an output pulse or other indication after receiving a specified number of input pulses.

CPU: *See* central processing unit.

CURRENT-MODE LOGIC: *See* CML.

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* Trademark of Motorola Inc.

CURRENT SINKING LOGIC: A logic family in which fanout is limited by how much current can sink through the output to ground, e.g., DTL and TTL.

CURRENT SOURCING LOGIC: A logic family in which fanout is limited by how much current the devices can source through the output from the supply to the driven inputs, e.g., RTL.

D-A: Digital-to-analog.

D-A DECODER: Digital-to-analog decoder for changing a digital word to an equivalent analog value.

DC AMPLIFIER: A direct-coupled multistage amplifier, which is highly desirable for designing integrated circuits because reactive components, such as inductances and high-value capacitances used for coupling, are difficult to fabricate.

DC FLIP-FLOP: Clocking is accomplished by an input voltage level rather than by a clock waveform edge. Clocking may be done by very slowly changing waveforms.

DCTL: Direct-coupled transistor logic, the first logic form that was considered for integrated circuits. (RTL is DCTL modified by the use of resistance coupling.)

DECADE COUNTER: A logic device that has 10 stable states. The device may be cycled through these 10 states with 10 clock or pulse inputs. A decade counter usually counts in a binary sequence from state 0 through 9 and then cycles back to 0. It is sometimes referred to as a divide-by-10 counter.

DECODER: A unit that translates a combination of signals into a single signal representing that combination. Often used to extract information from a complex signal.

DELAY TIME (PULSE *or* PROPAGATION): The time interval from a point at which the leading edge of the input pulse has risen to 10% of its maximum amplitude to a point at which the leading edge of the output pulse has risen to 10% of its maximum amplitude. (*Note:* Can be measured from 50% to 50% points instead of 10% to 10% points. Can also be measured from one input level to one output level such as 1.5 V).

DEMULTIPLEXER: A circuit which directs information from a single input to one of several outputs in a specific sequence determined by the information applied to the control inputs.

D FLIP-FLOP: *D* stands for delay. A *D* flip-flop is one whose output is a function of the input which appeared one pulse earlier, e.g., if a 1 appeared at the input, the output after the next clock pulse will be a 1.

DIFFERENTIAL AMPLIFIER: A circuit which amplifies the difference of potential between two input signals.

DIFFERENTIAL COMPARATOR: A circuit using differential-amplifier design techniques to compare an input voltage with a reference voltage. When the input voltage is below the reference, the circuit output is in one state; when the input voltage is above the reference, the output is in the opposite state. Commonly used for pulse amplitude detector circuits. A-D conversion, and differential twisted pair line receivers for data transmission in noisy environments.

DIFFUSION: A thermal process by which minute amounts of impurities are deliberately impregnated and distributed into semiconductor material.

DIGITAL CIRCUIT: A circuit which operates like a switch and can make logical decisions. It is used in computers or similar decision-making equipment. The more common families of digital integrated circuits (called *logic forms*) are RTL, DTL, HTL, ECL, and TTL.

DIGITIZE: The translation of a quantitative measurement into a coded numerical equivalent.

DISCRETE CIRCUITS: Circuits built of separate, individually manufactured, tested and assembled electronic components (transistors, diodes, resistors, etc.).

DIVIDE-BY-16 COUNTER: A logic device, containing four flip-flops, that will count from the binary number 0 through 15 and then recycle to 0. All 16 states of the four flip-flops are used. Sometimes referred to as a hexadecimal counter.

DOT: A dot, or bubble, drawn on the input of a logic symbol to indicate the active signal input is a negative input. The lack of a dot indicates a positive active signal.

DOT-AND: Externally connecting separate circuits or functions so that the combination of their outputs results in an AND function. The point at which the separate circuits are wired together will be a 1 if all circuits feeding into this point are 1. (Also called *wired-AND*.)

DOT-OR: Externally connecting separate circuits or functions so that the combination of their outputs results in an OR function. The point at which the separate circuits are wired together will be 1 if any of the circuits feeding into this point are 1. (Also called *wired-OR*).

DRIVER: A device in a logic family that can be controlled with normal logic levels while its output has the capability of sinking or sourcing high current. The output may control a lamp, relay, or a very large fanout of other logic devices. Also a device "driving" a higher output device or transistor by supplying power, voltage, or current to it.

DTL: Diode-transistor logic. The logic is done by diodes; the transistors are used as inverting amplifiers.

DUAL IN-LINE (PACKAGE): A container for a circuit, a package, having two parallel rows or lines of leads. This facilitates automatic insertion of the integrated circuit package on the assembly line.

DYNAMIC SHIFT REGISTER: A shift register that stores information using temporary charge-storage techniques. This results in simple register design, thus allowing the production of large, inexpensive shift registers. The major drawback of this technique is that the information is lost if the clock repetition rate is reduced below a minimum value.

ECL: Emitter-coupled logic, an unsaturated logic performed by emitter-coupled transistors. It was developed to achieve the ultra-high speeds required by advanced computers, unattainable with saturated logic circuits.

EDGE-TRIGGERED FLIP-FLOP: Changes state only during clock transition.

ELEMENT: A part of an integrated circuit which contributes directly to its electrical characteristics. An active element exhibits gain, as a transistor; a passive element does not have gain, such as a resistor or capacitor.

EMITTER-COUPLED LOGIC: *See* ECL.

ENCODER A unit which changes discrete inputs into coded combinations of outputs.

EXCLUSIVE-NOR (GATE): If one and *only* one of the inputs is true the output is *not* true.

EXCLUSIVE-OR (GATE): If one and *only* one of the inputs is true the output is true.

EXPANDABLE GATE: A logic gate for which the number of inputs can be expanded by the simple addition of an expander block.

EXPANDER: A logic block which can be easily connected to an expandable gate to increase the number of available logic inputs.

FAN-IN: The number of inputs connected to a gate.

FANOUT: The number of loads connected to a gate.

FANOUT (maximum): The worst-case number of loads a circuit can drive.

FLAT PACK: A description of a slab-shaped (*flat*) integrated circuit package (*pack*).

FLIP-FLOP: A digital circuit used to store information. The flip-flop has two stable states: 0 or 1. When the flip-flop is set to one of these states, it remains in that state until the application of a control signal causes it to "flip" or "flop" to the other state (0 or 1). Among the many kinds of flip-flops are delay (*D*), gating (*J-K*), set-reset (*R-S*), and toggle flip-flops.

FREQUENCY DIVIDER: A counter having a gating structure added to it for providing an output pulse after receiving a specified number of input pulses.

FREQUENCY SYNTHESIZER: A frequency-generating circuit that can produce a multitude of output frequencies from a single input frequency.

FULL ADDER: A logic device which will add two binary bits, taking into consideration the possible carry from a previous addition. Sum and carry outputs are provided.

FULL SUBTRACTOR: A device which can take the difference of two input bits, also subtract a borrow from those bits, and provide the difference and borrow outputs.

FUNCTION: A word description of what a given circuit does.

GATE: A ditital logic element with usually one output and many inputs, designed so that the output is enabled only when certain input conditions are met. The circuit then "gates," or passes, the desired signal.

GATED: The action in which data may be either passed or blocked along some path, depending on the level of a control input to the "gating" logic.

GRAY CODE: A binary code in which each number differs from the sequential numbers in one place—and in that place it differs by one unit.

HALF-ADDER: A logic element which will add two input bits. It has no provision for adding in the carry from a previous addition. (*See* full adder.)

HARDWARE: The physical components of a computer or a system. (*Software* is the term used to describe the programs and instructions for a computer.)

HEAT SINK: A mounting base for semiconductor devices, usually metallic, which serves to dissipate, carry away, or radiate into the surrounding atmosphere heat which is generated within a device. The device's package itself often serves as a heat sink for the semiconductor chip, but, for higher power devices, a separate heat sink on which one or more packages are mounted is required to prevent overheating, and subsequent destruction, of the semiconductor junctions.

HEXADECIMAL COUNTER: *See* divide-by-16 counter.

HEX INVERTER: Six logic inverters in a single package.

HTL: High-threshold logic, developed as the economical answer to the need for shielding circuitry from electrical noise in a system.

HYBRID CIRCUIT: Sometimes used to define multichip circuits in which two or more silicon chips are interconnected within one package. More often used to denote circuits made by two different processes (i.e., semiconductor and thick-film or thin-film) or by a combination of integrated structures and discrete components.

IC: *See* integrated circuit.

IF AMPLIFIER: An IF amplifier is an intermediate-frequency amplifier usually used in superheterodyne receivers. The IF amplifier normally operates somewhere between 100 kHz and 100 MHz. Most AM broadcast-band receivers have IF amplifiers at either 262 or 455 kHz. Most FM broadcast-band receivers have IF amplifiers at 10.7 MHz. The IF amplifier is used to provide high gain per stage and selectivity, both of which are more difficult to achieve at higher operating frequencies.

IMPLIED-AND *or* DOT-AND *or* WIRED-AND: The combined outputs are true if and only if all outputs are true.

IMPLIED-OR *or* WIRED-OR: The combined outputs are true if one or more of the outputs is true.

INHIBIT: To prevent an action or acceptance of data by applying an appropriate signal to the appropriate input (generally a logic 0 in positive logic).

INPUT: The signal (current, voltage, or power) fed into a circuit. Also, that point (terminal) at which the incoming signal is applied.

INTEGRATED CIRCUIT (IC): An integrated circuit is a tiny electrical device that is built into a single package and performs a complete circuit function. It replaces a given number of transistors, diodes, resistors, and capacitors that would be needed to perform the equivalent function.

INVERTER: A device that complements a logic variable, i.e., changes the logic levels from high to low or low to high. (Also called a *NOT* circuit.)

J-K FLIP-FLOP: A flip-flop having two inputs designated *J* and *K*. At the application of a clock pulse, a 1 on the *J* input and a 0 on the *K* input will set the flip-flop to the 1 state. A 1 on the *K* input and a 0 on the *J* input will reset it to the 0 state. 1s simultaneously on both inputs will cause the flip-flop to change state regardless of the previous stage; 0s simultaneously will prevent change.

JUNCTION: A boundary between *N*-type and *P*-type semiconductor material.

LARGE-SCALE INTEGRATION (LSI): A large number of interconnected integrated circuits manufactured simultaneously on a single slice of semiconductor material (usually over 100 gates or basic circuits, with at least 500 circuit elements).

LATCH: A very simple logic storage element. The most basic form is two cross-coupled logic gates which store a pulse presented to one logic input until the other input is pulsed, thus storing the complementary information in the latch.

LATCH VOLTAGE: The effective voltage on an input at which a flip-flop switches to its opposite state.

LEAD: One of the wires or pins on the outside of a semiconductor device, used to connect the device with a circuit.

LINEAR (*or* ANALOG) CIRCUIT: The linear circuit operates directly on a continuous electrical signal to change the signal's shape, increase its strength, or otherwise modify it for a specific end function. Typical linear circuits are operational amplifiers, differential amplifiers, sense amplifiers, regulators and multipliers, etc. Normally the output is some continuous (linear) function of the input and the device does not operate in saturation.

LINE DRIVER: An integrated circuit specifically designed to transmit logic information through long lines, normally several feet or more in length.

LINE RECEIVER: Used in conjunction with a line driver to detect signals at the receiving end of a long line.

LOGIC: A means of solving complex problems through the use of symbols to define basic concepts. (The three basic logic symbols are AND, OR, and NOT, NAND and NOR are combinations of the logic operations which those three basic symbols represent.)

LOGICAL OPERATIONS: Non arithmetical operations, such as selecting, searching, sorting, matching, comparing, etc.

LOGIC LEVEL: One of two possible states, or levels: 0 or 1.

LOGIC DIAGRAM: A drawing which represents the logical functions and AND, NAND, etc.

LOGIC SWING: The voltage difference between the two levels representing logical 1 and 0.

LSB: Least significant bit; the lowest weighted digit of a binary number.

LSI: *See* large-scale integration.

MAIN FRAME: The central processing unit of a computer plus the input/output unit and the random-access and read-only memories. The main frame is the computer without peripherals.

MAJORITY GATE: If more than half the number of inputs are true the output is true, otherwise the output is false.

MASTER/SLAVE FLIP-FLOP: A normally synchronous flip-flop which stores information in a master section on the one clock edge or level and transfers it to the slave section on the next clock edge or level.

METAL-OXIDE-SEMICONDUCTOR: A circuit in which the active region is a metal-oxide-semiconductor sandwich. The oxide acts as the dielectric insulator between the metal and the semiconductor. (*See* MOS.)

MICROCIRCUIT: Another name for integrated circuit.

MICROELECTRONICS: Refers to circuits built from miniaturized components and includes the broad category of integrated circuits.

MICRON: One-millionth of a meter.

MICROSECOND: One-millionth of a second.

MIL: One-thousandth of an inch.

MILLISECOND: One-thousandth of a second.

MINIMUM TOGGLE FREQUENCY: The guaranteed minimum toggle frequency of a flip-flop. The maximum toggle frequency for a typical device is usually about 20% higher.

MONOLITHIC: Refers to the single slice of silicon substrate on which an integrated circuit is built; hence, monolithic integrated circuit.

MONOSTABLE MULTIVIBRATOR: A logic element which has two states, one of which is stable and the other temporary. A monostable may be triggered into the temporary state where it will remain for a predetermined period of time before reverting to the stable state.

MOS: An acronym for metal-oxide-semiconductor. It is one of the solid-state technologies used for the fabricating of large, low-cost memories with very high input impedance. The insulator used is an oxide of the semiconductor substrate material. (*See* metal-oxide-semiconductor.)

MSB: Most significant bit; the highest weighted digit of a binary number.

MSI: Medium-scale integration. (*See* LSI.) Smaller than LSI, but having at least 12 gates or basic circuits with at least 100 circuit elements.

MULTIPLEXER (ANALOG *or* LINEAR): A device that can be used to select one out of a multiple number of inputs and switch its information to the output. The output voltage follows the input voltage with a small error. Field-effect and MOS devices are frequently used in this application.

MULTIPLEXER (DIGITAL): A device that can select one of its multiple inputs and pass that input logic level on to the output. Analog data cannot be handled (*only digital information*). Input channel select information is usually presented to the device in binary weighted form, and decoded internally, selecting the proper input. The device acts as a single-pole, multi-position switch that will pass digital information in only one direction.

MULTIPLEXING: The combining of a number of data lines into a single channel. Multiplexing has already reduced the tons of communications wiring normally used in modern jet liners to a single-wire system in the new 747s. (*See* multiplexer.)

MULTIPLIER, FOUR-QUADRANT: The linear, four-quadrant monolithic block that can multiply, double frequency, perform control functions, modulate, demodulate …… provide the correctly signed product for all four possible combinations of positive and negative values of its two inputs. The versatile four-quadrant multiplier can perform any function that can be expressed mathematically as the product of two quantities, generating such arithmetic functions as products, squares, quotients, and square roots.

MULTIVIBRATOR: A two-state device. (*See* monostable multivibrator.)

MUX: Multiplex.

NAND (GATE): An AND circuit that delivers and inverted output signal.

NANOSECOND (NS): One-billionth of a second, or one millimicrosecond.

NEGATIVE LOGIC: Logic in which the less positive voltage represents the 1 state. (Positive logic is that in which the more positive voltage stands for the 1 state.)

NEGATIVE VOLTAGE REGULATOR: A negative voltage regulator maintains a constant negative output voltage (*minus* with respect to ground), even with wide input voltage changes or variable output loading.

NOISE: Extraneous signals, any disturbance, which causes interference with the desired signal or operation.

NOISE IMMUNITY: How much insensitivity a logic circuit has to triggering or reaction to undesirable electrical signals or noise.

NOISE MARGIN: The amount of voltage of extraneous signal which can be tolerated before a circuit's output voltage deviates from the allowable logic voltage levels.

NOR (GATE): An OR circuit that delivers an inverted output signal.

NS: An abbreviation for nanosecond.

N-TYPE: A semiconductor may be one of two types: *N*-type means that an excess of negative charges are present; *P*-type semi-conductor has an excess of positive charges.

OCTAL NUMBERING SYSTEM: One which uses numbers with the radix (base) 8.

OFFSET: In digital circuits, offset is the d.c. voltage on which a signal is impressed. In a linear amplifier, offset is the input voltage change needed to cause a zero output voltage.

ONE-SHOT: A monostable device which when triggered by an external pulse or level will switch into the temporary state, holding the output at a given logic level until a predetermined time delay is up. At this time the output will revert to its stable state.

OP AMP: *See* operational amplifier.

OPEN-LOOP GAIN: The gain of an amplifier with no external feedback.

OPERATIONAL AMPLIFIER: An amplifier having high d.c., stability and high gain, high input impedance and low output impedance. Its operating characteristics are a function of external feedback components. They are used in such analog functions as summing amplifiers, integrators, function generators, gain blocks, etc. They are a common linear IC building block used in many systems applications.

OR (GATE): If one or more inputs is true the output is true.

OXIDATION: A chemical reaction in which a thin portion of the surface of a silicon wafer or slab is converted to silicon dioxide. In general, the conversion of any element to its oxide.

PACKAGE: The metal, ceramic, or plastic protective housing (cover) which encloses a semiconductor device or function.

PACKAGE COUNT: The number of packaged circuits within a subsystem or system.

PARALLEL OPERATION: Type of information transfer whereby all digits of a word are handled simultaneously, each bit being transmitted on separate lines in order to speed operation, as opposed to serial operation in which the bits are transmitted one at a time along a single line.

PARAMETER: A definable, stated constant, electrical characteristic of a device.

PARASITICS: Stray reactances or elements associated with the desired components diffused into an integrated circuit. Such parasitics may consist of capacitances, resistances, diodes or transistors effectively in series or in shunt with the diffused components. They tend to limit the performance of the desired components in a circuit unless compensated for in device and circuit design.

PASSIVE ELEMENTs: Those components in a circuit which have no gain characteristics, such as capacitors, resistors, and inductors. (*See* active elements.)

PCB: Printed circuit board.

PHASE DETECTOR: A circuit that provides an output signal indicating the relative phase, or timing difference between input signals. It is often used to operate a voltage-controlled oscillator, thus keeping it synchronized with a reference signal. (Also called *phase discriminator*.)

PHASE-LOCKED LOOP (PLL): A closed-loop electronic servo mechanism whose output will lock onto and track a reference signal. Phase lock is accomplished by comparing the phase of the output signal (or multiple thereof), with the phase of the reference signal. Any phase difference between these two signals is converted to a correction voltage that changes the phase of the output signal to make it track the reference.

PICOSECOND (PS): One-thousandth of a nanosecond.

PLL: *See* phase-locked loop.

POSITIVE LOGIC: Logic in which the more positive voltage stands for the 1 state. The less positive voltage represents the 0 state. (Negative logic is that in which the less positive voltage represents the 1 state.)

POSITIVE VOLTAGE REGULATOR: A positive voltage regulator operates from a plus supply voltage (referenced to ground) and keeps a constant positive output voltage even with wide changes in either input voltage or in output loading.

PRINTED CIRCUIT: A substrate on which a predetermined pattern of printed wiring and printed elements has been formed.

PROGRAMMABLE COUNTER: Also called *modulo N counter* as it can be logically programmed to count to any number from 0 to its maximum possible modulus.

PROPAGATION DELAY: The time difference between the application of a signal to a particular system or circuit and its appearance at the output of the system or circuit.

P-TYPE: A semiconductor may be one of two types: *P*-type semiconductor has an excess of positive charges; *N*-type means that an excess of negative charges are present in the semiconductor.

PULLDOWN RESISTOR A resistor connected to a negative voltage or ground.

PULLUP RESISTOR: A resistor connected to a positive supply voltage.

PULSE: A brief voltage or current surge of measurable duration (called *pulse width* or *pulse length*) and magnitude (called *pulse height* or *pulse amplitude*).

PULSE-TRIGGERED BINARY: A flip-flop that will change state when a pulse or waveform of short duration is applied to the input.

Q OUTPUT: The reference output of a flip-flop. When this output is 1, the flip-flop is said to be in the 1 state; when it is 0, the output is said to be in the 0 state.

$\bar{Q}$ (*Q*-bar) OUTPUT: The second output of a flip-flop. It is always opposite in logic level to the *Q* output.

QUAD LATCH: A group of four flip-flops, each of which can store a "true" or "false" level, and that are all normally enabled by a single control line. When the flip-flops are all enabled, new data may be stored in each of them.

QUIESCENT DISSIPATION: The power dissipated by a circuit when no dynamic signals are applied to the inputs or activating the circuitry.

RAM: *See* random access memory.

RANDOM ACCESS MEMORY (RAM): A memory that has the stored information immediately available when addressed, regardless of the previous memory address location. As the memory words can be selected in any order, there is equal access time to all.

READ-ONLY MEMORY (ROM): A memory which permits the reading of a predetermined pattern of 0s and 1s. This predetermined information is stored in the ROM at the time of its manufacture. A ROM is analogous to a dictionary, where a certain address results in predetermined information output. The information is available at any time, but it can not be modified during normal system operation.

READOUT: The manner in which a computer displays the processed information. May be digital, visual display, punched tape, punched cards, automatic typewriter, etc.

REGISTER: A short-term storage circuit whose capacity is usually one computer word. Certain variations may also include provisions for shifting, calculating, etc. (*See* static shift register, or dynamic shift register.)

REGULATOR: A regulator is a device used to maintain a desired output voltage or current constant regardless of normal changes to the input or to the output load.

RELIABILITY: The measure of a device's ability to function without failure over a period of time.

RESET: To return a memory or storage element to its "standard" state, usually 0. Also called *clear*.

RF AMPLIFIER: An RF amplifier is a radio-frequency amplifier normally operating at a higher frequency than an IF or intermediate-frequency amplifier. It is used for signal isolation, to provide gain for the signal so that it is amplified above the noise level, and to provide input selectivity to a receiver. The RF stage is normally the first stage of amplification in a radio receiver.

RING COUNTER: A sequential closed loop of flip-flops. A pattern of binary bits is shifted around the loop (ring) by a common clock. There are usually *n* (equal to the number of flip-flops) unique states or counts. A ring counter is often used to control a sequence of *n* events.

RIPPLE: Serial transmission of data, corresponding to the way a row of dominoes falls after the first domino has been felled.

ROM: *See* read-only memory.

R-S FLIP-FLOP: A flip-flop consisting of two cross-coupled NAND gates having two inputs designated *R* and *S*. A 1 on the *S* input and 0 on the *R* input will reset (clear) the flip-flop to the 0 state; 1 on the *R* input and 0 on the *S* input will set it to 1. It is assumed that 0s will never appear simultaneously at both inputs. If both inputs have 1s, it will stay as it was. 1 is considered non-activating.

R-S-T FLIP-FLOP: A flip-flop having three inputs: *R*, *S*, and *T*. It works as the *R-S* flip-flop except that the *T* input is used to cause the flip-flop to change states.

RTL: Resistor-transistor logic, developed to overcome the problem of variations in the base-emitter voltage of DCTL, the forerunner of RTL. In RTL, the logic is done by resistors, while the transistors are used to amplify and obtain an inverted output from any positive input.

SATURATED LOGIC: A form of logic in which one output state is the saturation voltage of a transistor, e.g., resistor-transistor logic (RTL), diode-transistor logic (DTL), and transistor-transistor logic (TTL). (*See* unsaturated logic.)

SCHEMATIC: A diagram of a circuit in which symbols are used to stand for the circuit's basic components.

SCHMITT TRIGGER: A binary circuit that can take a slowly changing input waveform and convert it to an output waveform which has sharp transitions. Normally hysteresis is present between an upper triggering and a lower triggering level.

SCHOTTKY BARRIER: A simple metal semiconductor interface which exhibits nonlinear impedance.

SEMICONDUCTOR: Materials may be classified as one of three types by resistivity—low resistivity materials are called *conductors*; very high resistivity materials are called *insulators* or *dielectrics*; materials with intermediate resistivities are called *semiconductors*—examples are germanium and silicon.

SERIAL OPERATION: Type of information transfer within a digital computer whereby the bits are handled sequentially rather than simultaneously, as in parallel operation. Serial operation is slower than parallel operation, but utilizes less complex circuitry.

SET (as opposed to clear): An input on a flip-flop used to affect the *Q* output. It is this input through which signals can be entered to get the *Q* output to go from 0 to 1. It cannot get *Q* to go to 0.

SHIFT REGISTER: A digital storage circuit which uses a chain of flip-flops to shift data from one flip-flop to its adjacent flip-flop on each clock pulse. Data may be shifted several places to the right or to the left depending on additional gating and the number of clock pulses received. Depending on the number of positions shifted, in a right shift the rightmost characters are lost; in a left shift the leftmost characters are lost. (*Also see* dynamic shift register *and* static shift register.)

SINGLE-SHOT MULTIVIBRATOR: A monostable multivibrator which, after being triggered to the quasi-stable state, will "flop" back by itself to the stable state after a certain period of time.

SKEWING: Refers to time delay or offset between any two signals in relation to each other.

SLEW RATE: The maximum speed with which an output can be driven from one limit of the dynamic range to the other.

SLICE: A single wafer or slab, one of many cut from a silicon ingot to form the thin substrate on which semiconductors are fabricated. After processing, the slice may contain up to hundreds or thousands of semiconductor dice.

STATE: The logic 0 or 1 condition of a circuit's output.

STATIC SHIFT REGISTER: A shift register that uses logic flip-flops for storage. The technique in integrated form results in larger storage cell size and therefore shorter shift register lengths. Its primary advantage is that information will be retained as long as the power supply is connected to the device. A minimum clock rate is not required; in fact, it can be unclocked.

SWITCH-TAIL RING COUNTER: A type of ring counter where one stage has its output inverted before providing an input to the next stage. An even number of states equal to $2n$ (n is equal to the number of flip-flops) is normally generated. For example: A modulo 10 counter can be built from five flip-flops. Each flip-flop changes states once every five counts. Decoding of all 10 states is easily accomplished with 10 two-input gates.

SYNCHRONOUS OPERATION: The performance of a switching network, wherein all major circuits in the network are switched simultaneously by a clock pulse generator.

T FLIP-FLOP: A flip-flop having only one input. A pulse appearing on the input will cause the flip-flop to change states.

THRESHOLD VOLTAGE: That input voltage level at which a binary circuit goes from one logic level to the other, e.g., 0 to 1, or 1 to 0.

TOGGLE: To switch back and forth between two states, as in a flip-flop. (Like a toggle switch.)

TOGGLE FLIP-FLOP: *See* flip-flop.

TRIGGER: A timing pulse which initiates logic circuit operations.

TRUTH TABLE: A tabular chart which lists all the possible combinations of the inputs and outputs of a circuit.

TTL (T^2L): Transistor-transistor logic, which was evolved from a desire for more speed than was possible with DTL. DTL was modified by replacement of the diode cluster with a multiple-emitter transistor.

TWO-PHASE DYNAMIC: Dynamic logic circuits using two clock signals to control the progress of information through the circuit or logic system.

UNSATURATED LOGIC: A form of logic with transistors operated outside the saturated region, e.g.: current-mode logic (CML) and emitter-coupled logic (ECL). (*See* saturated logic.)

UP-DOWN COUNTER: A counter which can count in either an ascending or descending order.

VOLTAGE COMPARATOR: A circuit that compares two analog voltages and generates a logic output when the two voltages are equal or one is greater or lesser than the reference. (*See* comparator.)

VOLTAGE REGULATOR: A circuit which keeps an output voltage at a predetermined value, or which varies the voltage according to a predetermined plan, regardless of normal voltage changes to the input or impedance changes in the output load.

WAFER: The thin slice or flat disc of silicon sliced from a silicon ingot, on which integrated circuits and other semiconductor devices are simultaneously fabricated. (*Also see* slice.)

WIRED-AND: *See* DOT-AND.

WIRED-OR: *See* DOT-OR.

APPENDIX C

MISCELLANEOUS HARDER PROBLEMS

Emission of Electrons

1. Calculate the operating characteristics and life for a 10% evaporation of mass of an ideal tungsten filament having a length of 2 cm and a diameter of 2.5 mm when operated at a temperature of 2,600°K. Use the data given in the table which has been published by Jones and Hangmuir for an ideal tungsten filament 1 cm long and 1 cm diameter. The density of the material is 19.

Filament Temperature	Filament Details					
	Heating watts W'	Resistance R_f'	Current I_f'	Voltage V_f'	Emission current I_e'	Evaporation M' in grams/cm^2/s
2600°K	263.0 W	$98.66\times 10^{-6}\,\Omega$	1632 A	161.1×10^{-3} V	2.25 A	2.76×10^{-8}

[Ans. Power radiated 13.17 W; Resistance 0.3155 Ω, Filament current 6.45 A, Voltage drop 2.04 V, Emission current 0.1125 A; 376 hours.)

2. A certain thoriated-tungsten filament operating at 1900°K gave a saturation current of 85 mA. Calculate the corresponding current for a pure-tungsten filament of the same area operating at 2,500°K. The Dushman constants are:

For thoriated tungsten, $A=3.0$ amps/cm^2(°K)^2; $b=30{,}500$°K

For pure tungsten, $A=60.2$ amps/cm^2(°K)^2; $b=52{,}400$°K.

(Ans. 21.8 mA)

3. Calculate the space-charge-limited current density between parallel plates 2 mm apart when the voltage across them is 200 V.

(Ans. 165 mA/sq. cm)

4 A certain filament operating at 2,100°K was thought to give a saturation current 10,000 times as great as that when the operating temperature was 1,600°K. If this had been true what would the work function of the filament material have been.

(Ans. 5 V)

5. Two diodes each have an anode 4 mm in diameter and 2 cm long, but one of them has a filament 0.1 mm in diameter, while the other has an indirectly-heated cathode 1.5 mm in diameter. Calculate the space currents flowing in each valve when the anode voltage is 25 V. (Ans. 17 mA, 41 mA)

Circuit Theory

6. A coil of inductance 88 μH is placed in series with a 4.8 Ω resistor. The combination is connected in parallel with a 375 pF (i.e., 375 $\mu\mu$F) capacitor. Calculate the frequency of the circuit for which the effective impedance is a pure resistance.

(Ans. 876.4 kHz)

7. A series *L*, *C*, *R* circuit, with $R=4\ \Omega$, $L=100\ \mu$H and $C=200$ pF is connected to a constant-voltage generator of variable frequency. Calculate the resonant frequency, the value of '*Q*' and the frequencies at which half the maximum power is delivered. (Ans. 1126 kHz; 177; 1129 kHz; 1122 kHz)

8. A parall elresonant circuit employs a 50 pF capacitor and has a bandwidth of 250 kHz. Calculate the maximum impedance of the circuit.

(Ans. 12,740Ω)

9. A parallel resonant circuit is tuned to a frequency of 1 MHz and contains a 200 pF capacitor. When a source of constant voltage is injected in series with the circuit the current falls to 0.707 of its resonant value, for a frequency deviation of 5 kHz from the resonant frequency. Calculate the circuit '*Q*' and the parallel resonant impedance.

(Ans. 100; 79.6 KΩ)

10. Two-series circuits, each consisting of a 300 μH inductor and a 1000 pF capacitor, are magnetically coupled so as to have a mutual inductance of 60 μH. An e.m.f. of 10 V having a frequency of $1/\pi$ MHz is injected into one circuit. Determine the current in the other circuit and the coefficient of coupling (k).

(Ans. $-$j 0.273A; 0.2)

11. A coil has an inductance of 5 mH, a self-capacitance of 5 pF and a high-frequency resistance of 100 Ω. Determine the effective resistance and inductance of the coil at a frequency of 500 kHz. (Ans. 177 Ω, 6.67 mH)

12. A wavemeter consists of a variable capacitor, having a range of 50 to 1,000 pF and two coils of inductances 300 and 100 μH respectively. If the coils are fixed so that their mutual inductance is 25 μH, what range will the wavemeter have when the coils are used (a) in series aiding, (b) in series opposing, (c) in parallel aiding and (d) in parallel opposing?

(Ans. (a) 283 to 1265 m, (b) 249 to 1115 m, (c) 122 to 546 m, (d) 107 to 481 m)

13. A transformer has a tuned primary winding and an untuned secondary. The inductance of each winding is 1 mH and the mutual inductance between them is 0.5 mH. The primary winding is tuned with secondary open-circuited, and resonates at a frequency of 500 kHz. If the secondary is now short-circuited find the change of tuning capacitance required to keep the same resonant frequency. Neglect the resistances of the windings.

(Ans. 34 pF)

14. Two coils of inductances 50 μH and 200 μH respectively, are magnetically coupled. Find the effective value of the mutual inductance between them, at a frequency of 2 MHz, their self capacitances being 5 and 7 pF respectively and the coefficient of coupling being 0.05.

(Ans. 6.3 μH)

15. A coil is tuned to a certain frequency by a 250 pF capacitor. To tune the coil to the second harmonic of this frequency a capacitance of 55 pF is required. Determine the self capacitance of the coil.

(Ans. 10 pF)

16. The series resistance bridge network is used for the comparison of capacitances. A capacitor of capacitance C_1 and equivalent series resistance ρ_1 is compared with a standard air capacitor of capacitance 0.023 μF and zero equivalent resistance. When a balance is obtained the resistor in series with C_1 has a value of 11.4 Ω and that in series with the standard capacitor has a value of 10 Ω. The non-inductive resistors have values of 1,000 Ω and 1,250 Ω, one end of the latter being connected to one side of C_1. Calculate ρ_1 and C_1.

(Ans. 1.1 Ω, 0.0184 μF)

17. A schering bridge is used for measuring the power loss in dielectrics. The specimens are in the form of discs 0.3 cm thick and have a dielectric constant of 2.3. The area of each electrode is 314 cm^2 and the loss angle is known to be 9′ for a frequency of 50 Hz. The fixed resistor of the network has a value of 1,000 Ω and the fixed capacitance is 50 pF. Determine the values of the variable resistor and capacitor required.

(Ans. 4,260 Ω, 0.00196 μF)

Vacuum Tubes

18. The anode-voltage/anode-current characteristic of a certain diode is given by the following figures:

Voltage (V)	0	5	10	15	20	25	30	35
Current (mA)	0	3.1	8.9	17.0	26.8	38	51.4	66

Plot the dynamic characteristic curve if the load has a resistance of 2500 Ω. Hence find the load current and the voltage across the load when the supply voltage is 50 V. (Ans. 14.5 mA, 36.25 V)

19. A diode valve has the following anode-current/anode-voltage characteristic:

Current (mA)	0.52	1.17	1.90	2.78	3.85	5.15	6.50
Voltage (V)	25	50	75	100	125	150	175

The valve is placed in series with a resistor of 20,000 Ω and a battery of 200 V. A resistor of 60,000 Ω is connected between the anode and cathode of the diode. Determine the current through the diode. (Ans. 3 mA)

20. In tests on a certain thyratron, with a steady value of negative grid voltage applied to the valve, the anode voltage was gradually raised until the valve conducted. The corresponding grid and anode voltages at the point of conduction were:

Grid voltage (V)	−8.7	−8.0	−7.0	−6.0	−5.0	−4.0	−3.0	−2.0	−1.0	−0.5
Anode voltage (V)	191	176	152	131	109	88	66	46	34.2	33.8

Plot the control characteristic and estimate the control ratio over that portion of the graph which is approximately linear. (Ans. 21.8)

21. A thyratron just becomes conducting with 200 V on the anode when the negative grid voltage is held at −8 V. The control ratio is 35. Find the minimum anode voltage for conduction when the grid is held at −20 V. Determine also the critical gird voltage, when the anode voltage is 340 V. (Ans. 620 V, −12 V)

22. Three triodes having amplification factors of 10, 20 and 30 and with mutual conductances 2, 5 and 3 mA/V respectively, are operated in parallel. Calculate the equivalent mutual conductance, the anode resistance and the amplification factor of the combination. (Ans. 10 mA/V, 1818 Ω, 18.18)

23. The linear parts of the control characteristics of a certain thyratron are given by the following expressions:

$V_a=[-120\ V_g-160]$, when the temperature is 40°C

and $V_a=[-70\ V_g-130]$, when the temperature is 70°C

where V_a is the anode voltage in volts and V_g is the grid voltage in volts.

Evaluate for an anode voltage of 400 volts, the change in critical grid voltage when the temperature of the valve rises from 40°C to 70°C.

(Ans. 2.8 V)

Photoelectricity

24. Find the sensitivity of a photomultiplier which has six stages, if the gain/stage is 5 and the cathode sensitivity is 24 μA / lumen. If the maximum safe output current is 3 mA calculate the maximum safe illumination.

(Ans. 375 mA/lumen, 8 millilumens)

25. Show that for photoelectric emission to be possible over the whole visible region, 4,000 to 8,000 Å†, the work function of the photosensitive surface must be less than 1.55 ev.

Determine the threshold wavelength in the case of a caesium surface for which the work function is 1.8 ev.

Determine also the maximum velocity of the emitted photo electrons when a molybdenum surface, having a work function of 4.3 ev, is irradiated with the mercury line 2,537 Å.

(Ans. 6,890 Å, 4.56×10^5 m/s)

26. In an experiment on the photoelectric effect using radiation of wavelength 4×10^{-7} m, the maximum electron energy was observed to be 1.40×10^{-19} J. With radiation of wavelength 3×10^{-7}, the maximum energy was 3.06×10^{-19} J. If the velocity of light is 3×10^8 m/s, calculate the Plank's constant.

(Ans. 6.64×10^{-34} J.s.)

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† Preferably used SI unit 1 Å$=10^{-1}$ nm

Cathode-ray Oscillograph

27. A certain linear time base employs a saturated diode and a thyratron. The striking and extinction voltages of the thyratron are 280 V and 30 V respectively, and the diode charging current is constant at 5 mA. Find the range of capacitance values required for the capacitor if the sweep frequency is to be variable from 20 Hz to 20 kHz. (Ans. 0.001 to 1 μF)

28. A series circuit consisting of a 2,500 Ω resistor and a 4 μF capacitor is connected to a 300-V d.c. supply. Across the capacitor is a glow discharge tube which is triggered to strike every 20 ms. The tube on striking discharges the capacitor completely in a negligbly short time. Determine the r.m.s. value of the charging current.

Find also the voltage across the capacitor when the tube strikes. (Ans. 60 mA, 260 V)

29. A cathode-ray tube is constructed with internally mounted plane-parallel magnetic poles 1.5 cm long and the ends of these are a distance of 20 cm from the screen. Before entering the field due to the poles the electrons are accelerated by a voltage of 1,500 V. Determine the sensitivity of the tube in Wb/m^2/m. Neglect any fringing of the magnetic field (Ans. 0.042)

30. A cathode-ray tube has plane parallel deflector plates 1.5 cm long spaced 0.3 cm apart. The screen is 20 cm from the ends of the deflector plates. Before entering the space between the plates the electron beam is accelerated by a voltage of 1,500 V. Determine the sensitivity of the tube in volts/cm. Neglect any fringing at the ends of the deflector plates. (Ans. 28.9)

Rectifiers and Filters

31. A high-vacuum diode, with an internal resistance of 150 Ω, supplies power to a 1,000 Ω load from a 300-V r.m.s. source. Find: (i) the mean load current, (ii) the r.m.s. alternating load current, (iii) the d.c. power supplied to the load, (iv) the input power to the anode circuit, (v) the rectification efficiency and (vi) the ripple factor.

(Ans. (i) 117 mamps, (ii) 184 mamps, (iii) 13.8 W, (iv) 39.1 W, (v) 35.3%, (vi) 1.21)

32. Calculate the regulation and efficiency for a half-wave rectifier circuit, from no load to 80 mamps. The transformer r.m.s. secondary voltage is 230 V and the internal resistance of the diode is 500 Ω. Find also the current at which maximum power is obtained. (Ans. 40 V, 40.6 to 24.9%, 103.5 mamps)

33. A moving-iron ammeter and a simple moving-coil ammeter are placed in series with the load in a half-wave rectifier circuit. The reading on the a.c. instrument is 5 A. What is the reading of the other ammeter?

Calculate the instrument readings if the other half-wave is also rectified. Assume sinusoidal waveforms.

(Ans. 3.18 A, 7.07 A, 6.37 A)

34. A gas diode for which the striking and extinction voltages may both be taken as 10 V, supplies power in a half-wave rectifier circuit to a 1000 Ω load from a 300-V r.m.s. source. Calculate: (i) the mean load voltage, (ii) the d.c. power supplied to the load, (iii) the input power to the anode circuit, (iv) the rectification efficiency and (v) the ripple factor.

(Ans. (i) 130 V, (ii) 16.9 W, (iii) 43.7 W, (iv) 38.7%, (v) 1.225)

35. A full-wave single phase rectifier employs a double diode valve, the internal resistance of each element of which may be assumed constant at 500 Ω. The transformer r.m.s. secondary voltage from the centre tap to each anode is 300 V and the load has a resistance of 2,000 Ω. Evaluate: (i) the mean load current, (ii) the r.m.s. alternating load current, (iii) the d.c. output power, (iv) the input power to the anode circuit, (v) the rectification efficiency, (vi) the ripple factor and (vii) the regulation from no-load to the given load.

(Ans. (i) 108 mamps, (ii) 120 mamps, (iii) 23.3 W, (iv) 36 W, (v) 64.8%, (vi) 0.482, (vii) 54 V)

36. The rectifying element of a single-phase half-wave rectifier circuit has a resistance of 10 Ω in the forward direction and its resistance in the reverse direction may be taken as infinite. A resistor and a capacitor in parallel from the load and the capacitance is so great that the voltage across it is practically constant during both the charging and discharging periods. The resistance of the load is such that current flows through the rectifying element for one-sixth of each cycle of the a.c. supply voltage.

Determine the resistance of the load and the efficiency of rectification.

(Ans. 585 Ω, 89.4%)

37. In a full-wave rectifier circuit, employing a 20-H choke in a π-section filter, what would be the power dissipated in a resistor R which replaced the choke and gave the same ripple factor, with an output current of 100 mA? The supply frequency should be taken as (i) 50 c/s, (ii) 60 c/s.

Repeat the calculation for the case where the output current is only 10 mA. (Ans. (i) 125.7 W, 1.257 W, (iii) 150.8 W, 1.508 W)

38. A single-phase full wave rectifier circuit, employing a single L-type filter, is to supply 120 mA at 300 V with a ripple that must not exceed 10 V. Design a suitable filter if the supply frequency is (i) 50 Hz, (ii) 60 Hz.

(Ans. A 10-H choke and a 4-μF capacitor are suitable for both the cases.)

Amplifiers

39. A low frequency amplifier has a gain of 60 dB. The input circuit is of 600 Ω resistive impedance and the output is arranged for a load of 10 Ω. What will be the current in the load when an alternating voltage of 1 V is applied at the input?

Express the gain of the amplifier in nepers.

(Ans. 12.9 amps, 6.9 nepers)

40. A certain triode operates with an anode voltage of 250 V and a grid voltage of -8 V. The anode current is then 9 mA. If the valve is used with a load having a resistance of 10,000 Ω what is the value of supply voltage required?

If the H. T. supply voltage is fixed at 430 V, calculate the resistance of the load to keep the valve working at the same operating point. (Ans. 340 V, 20 K).

41. A voltage amplifier employs a valve operating with an anode current of 9 mA and a negative bias of 8 V. Find the value of the resistance of a cathode resistor to give the required bias.

Determine also a suitable value for the cathode bypass capacitance, if the signal frequency is (a) 1000 Hz, or (b) 100 Hz.

(Ans. 889 Ω; 2 μF, 20 μF)

42. The first stage of a resistor-capacitor coupled amplifier employs a valve with an amplification factor of 20 and an anode resistance of 7,700 Ω. The resistance of the load is 50,000 Ω, the coupling capacitor has a capacitance of 0.01 μF and the grid leak (including the resistive component of the input impedance of the next stage) has a resistance of 5,00,000 Ω. The input capacitance of the next stage is 200 pF. Evaluate the gain of the stage at intermediate frequencies.

Find also the frequencies at which the gain falls to $1/\sqrt{2}$ of its intermediate frequency value and calculate the frequency range over which the gain is greater than 14.

(Ans. -17.1, 31 Hz; 121,000 Hz; 44 to 84, 960 Hz)

43. Assuming the characteristic curves for a triode valve to be equidistant straight lines, prove that the maximum possible anode circuit efficiency for a class *A* amplifier, coupled to a resistive load through an ideal transformer, is 50%.

Show also that the theoretical maximum efficiency for the simple series-fed, class *A*, power amplifier is 25%.

44. A triode valve operates from a 300-V supply and its load is a resistor of 2,000 Ω coupled through an ideal transformer of ratio 1 : 1. When a sinusoidal voltage is applied between the grid and the cathode of the valve, the maximum and minimum values of anode current are 150 mA and 20 mA. When the alternating grid voltage is zero, the anode current is 80 mA. Determine the power delivered to the load, the efficiency and the approximate percentage of second harmonic current.

(Ans. 4.23 W, 0.17, 3.85%)

45. A transformer coupled amplifier has the following constants:

Amplification factor of the valve = 10.
Anode resistance of the valve = 8,000 Ω.
Ratio of secondary to primary turns of transformer = 3.
Effective leakage inductance of transformer referred to primary = 0.5 H.
Total effective shunt capacitance of transformer referred to primary = 1,000 pF.
Total effective resistance of transformer referred to primary = 15,000 Ω.
Resistance of primary winding of transformer = 3500 Ω.
Inductance of primary winding of transformer = 70 H.

Obtain a curve showing how the gain of the amplifier varies with frequency.

46. A triode in an amplifier has an anode resistance of 8,000 Ω and an amplification factor of 16. It is coupled to the following stage by a transformer with a step-up ratio of 3. The secondary of the transformer is loaded with a resistance of 450 K. Calculate the stage gain at a frequency where the primary reactance is 5 K.

(Ans. 24.3)

47. A certain audio frequency amplifier has a normal gain of 120 and gives an output voltage of 60 V to its output transformer, with 10% second-harmonic distortion. How much feedback must be used to reduce the distortion to 1%? Find also the additional gain required ahead of the feedback amplifier, in order to give the same output voltage.

(Ans. Feedback factor = -0.075, 10)

48. An amplifier has a gain of 20 without feedback. If 10% of the output voltage is fedback by means of a resistive negative-feedback circuit, determine the actual amplicafication. (Ans. 6.67)

49. A multistage amplifier, when operated without feedback and with normal supply voltage, has a gain of 24,000. When the supply voltage falls by 25% the amplification is only 16,000. Show that if a negative-feedback potentiometer across the output is used to feedback 1/1,000 of the output voltage to the input, the amplification is nearly independent of variations in supply voltage.

50. An amplifier employing a pentode with an amplification factor of 1000 and a mutual conductance of 5 mA/V has a 200-K load resistor. Calculate the voltage amplification (i) without feedback, (ii) with 5% negative voltage feedback.

Determine also the effective constants of the valve when feedback is used. (Ans. 500, $\mu'=19.6$, $r_p'=3.92$ K, $g_m'=5$ mA/V)

Show that the output impedance of a cathode-follower stage, which employs a valve with a mutual conductance of 4 mA/V, is about 250 Ω but the input impedance is high.

Oscillators

51. Using a certain triode, having an amplification factor of 5 and an anode resistance of 1800 Ω, it is desired to generate a frequency of 25 Hz in a tuned anode circuit. Two coils, each of 0.6 H inductance and 11 Ω resistance, are available, the maximum attainable coupling between them being 32%. Can the required oscillations be produced with this arrangement?

What is the lowest frequency at which the circuit will oscillate?

(Ans. No, 48.3 Hz)

52. A screen grid valve has a negative anode resistance r_p of 90,000 Ω with suitable anode and screen voltages and it is to be used with a coil L of 150 μH and a capacitor C of 500 pF capacitance to form a dynatron oscillator. Find the maximum coil resistance R to permit oscillation and the corresponding frequency.

(Ans. 3.33 Ω, 581 kHz)

53. A certain triode with an amplification factor of 9 has an anode resistance of 11,000 Ω when the anode and grid voltages are 90 V and -6 V respectively, and an anode resistance of 9,000 Ω when the anode and grid voltages are 135 V and -9 V respectively. A tuned anode circuit has $L=175\ \mu$H, $C=220$ pF and $R=18\ \Omega$. The grid coil has an inductance of 60 μH. With the higher anode voltage, what coefficient of coupling is required between the coils to make the circuit oscillate? How much must the coupling be if the anode voltage is dropped to 90 V and the bias adjusted accordingly? (Ans. 0.228, 0.237)

54. A triode with an amplification factor of 9 and an anode resistance of 11,000 Ω has a tuned grid circuit with constants of values $L=180\ \mu$H, $R=26\Omega$ and $C=0.0012\ \mu$F. The coil in the anode circuit has an inductance of 50 μH and a coupling of 30% to the grid circuit. Will the circuit oscillate?. (Ans. No)

55. A triode with an amplification factor 8 and an anode resistance of 6,000 Ω has a tuned anode circuit of $L=200\ \mu$H, $R=8\ \Omega$ and $C=0.0005\ \mu$F. The grid coil has an inductance of 35 μH. The maximum available coupling is 40%. To the tuned circuit is coupled a tuned aerial having a resistance of 24 Ω. Determine the maximum permissible mutual inductance between the aerial and the tuned circuit if oscillations are to be maintained.

(Ans. 5.94 μH)

56. In a class A Hartley oscillator the two sections of the coil have inductances of 45 mH and 15 mH, the latter being in the grid circuit. The capacitor has a capacitance of 0.2 μF. The amplification factor of the valve is 20. Neglecting losses, calculate the critical mutual inductance for maintaining oscillations.

(Ans. 13.42 mH)

57. A three-section ladder phase-shift oscillator has three similar phase-advancing sections, each consisting of a 100 K resistor and a 0.0005 μF capacitor. Calculate the frequency of oscillation and show that the attenuation ratio of the network is 29. (Ans. 1,300 Hz)

58. In a certain Wien bridge type of oscillator the frequency selective network employs 120,000 Ω resistors and 0.001 μF capacitors. Find the frequency of oscillation. (Ans. 1,326 Hz)

Modulation and Detection

59. The aerial current of a transmitter is 8 A when the carrier only is transmitted but it increases to 8.93 A when the carrier is sinusoidally modulated. Find the percentage modulation.

Determine the aerial current when the depth of modulation is 0.8. (Ans. 70%, 9.19 A)

60. The tuned circuit of an oscillator in an amplitude modulated transmitter employs a 50-μH coil and a 0.001-μF capacitor. If the oscillator output is modulated up to 10,000 Hz, what is the frequency range occupied by the carrier and sidebands?

(Ans. 702 to 722 kHz)

61. A certain transmitter radiates 9 KW of power with the carrier unmodulated and 10.125 KW when the carrier is sinusoidally modulated. Calculate the depth of modulation.

If another audio wave, modulated to 40%, is also transmitted, determine the radiated power. (Ans. 0.5, 10.845 KW)

62. If a radio-frequency carrier wave is amplitude modulated by a band of frequencies, 300 Hz to 3.4 kHz, what will be the bandwidth of the transmission and what frequencies will be present in the transmitted wave if the carrier frequency is 104 kHz?

(Ans. 6.8 kHz, 100.6 to 103.7 kHz, 104 kHz, 104 to 107.4 kHz)

63. A diode detector employs a 220 K resistor and a 100 pF capacitor. Calculate the maximum value of the depth of modulation if peak clipping is to be avoided and the maximum modulating frequency which the detector is designed to handle is 6,000 Hz.

(Ans. 0.77)

Transistors

64. The characteristics of a junction transistor are given in the following Table:

Collector voltage V_{CE}(volts)	Collector current (I_C) in mA		
	$I_B=0$	$I_B=40\ \mu$A	$I_B=80\ \mu$A
1	0.2	1.90	3.7
4	0.3	2.05	4.0
7	0.4	2.20	4.3

The transistor is connected in a common-emitter stage with a collector load of 1,500 Ω, to supply voltage of 6 V and a d.c.

bias of 40 μA. Plot the characteristics, draw the appropriate load line and calculate the power dissipated in the transistor.

What will be the total voltage swing at the collector for an a.c. input signal current of 40 μA peak in the base?

(Ans. 6 mW, 4.9 V)

65. For a transistor used in the common-emitter configuration the relationship between collector current and collector voltage, with various fixed values of base current, are given in the following Table:

Collector voltage(V)	Collector current (mA)				
	Base current −30 μA	Base current −50 μA	Base current −70 μA	Base current −90 μA	Base current −110 μA
−2	−0.9	−1.55	−2.2	−2.85	−3.55
−4	−0.92	−1.65	−2.4	−3.05	−3.77
−6	−0.95	−1.77	−2.55	−3.25	−4.0
−8	−0.98	−1.90	−2.75	−3.5	−4.2

Draw the static characteristics of the transistor and use these to determine the current gain when the collector voltage is −5 V.

The transistor is to be used as a common-emitter amplifier with a load resistance of 1,800 Ω and a collector battery voltage of −9 V. Draw the load line and use this to find the base current for a collector voltage of −4 V.

(Ans. 37, 82 μA)

66. The current amplification factor α of a common-base junction transistor operating at a frequency f is given by:

$$\alpha=\alpha_o\left\{\frac{1}{1+j(f/f\alpha)}\right\}$$

where α_o is the low frequency value of α and $f\alpha$, called the alpha cut-off frequency, is that frequency where $\alpha=\alpha_o/\sqrt{2}$.

Derive a corresponding expression for the current amplification factor when the transistor is used in the common-emitter configuration and give the corresponding cut-off frequency in terms of α_o and $f\alpha$.

$$\left(\text{Ans. } \frac{\alpha_o}{(1-\alpha_o)+j(f/f\alpha)},\ f\alpha(1-\alpha_o)\right)$$

67. A transistor has a current amplification factor of 0.96 at low frequencies and the alpha cut-off frequency is 5 MHz. Determine the current amplification factor at 10 MHz and calculate the frequency at which the current amplification factor falls to 0.6. (Ans. 0.43, 6.25 MHz)

68. The hybrid parameters of a certain transistor are:

$h_{11}=35\,\Omega$, $h_{21}=-0.976$, $h_{22}=1.0\,\mu$mhos and $h_{12}=7\times10^{-4}$.

Calculate the values of r_{11}, r_{12}, r_{21}, r_{22} and α.

(Ans. 718.2 Ω, 700 Ω, 976 KΩ, 1 MΩ, 0.976)

69. A junction transistor whose parameters are $r_{11}=820\,\Omega$, $r_{12}=800\,\Omega$, $r_{21}=1.98$ MΩ and $r_{22}=2$ MΩ is used in a single-stage, common emitter amplifier, with a load resistance of 430 Ω.

Calculte the voltage gain, the current gain and the input resistance. (Ans. -15.2, 99, 2755 Ω)

70. A junction transistor has the following constants: $r_{11}=550\,\Omega$, $r_{12}=500\,\Omega$, $r_{21}=1.9$ MΩ, $r_{22}=2$ MΩ. Determine the input resistance of a common base amplifier stage using this transistor as the load resistance varies from zero to infinity.

If the resistance of the source at the input of the amplifier is zero find the output resistance of the arrangement.

Calculate also the maximum possible voltage gain.

(Ans. 75 to 550 Ω, $2.72\times10^{5}\,\Omega$, 3454)

71. The hybrid parameters for a common emitter transistor amplifier circuit are $h'_{11}=800\,\Omega$, $h'_{21}=47$, $h'_{12}=5.4\times10^{-4}$ and $h'_{22}=80\,\mu$mhos. The load resistance is 20 K. Calculate the voltage and current gains. (Ans. -598, 18)

ANSWERS TO SELF-TEST

CHAPTER 1

(a) 4.80298×10^{-10} e.s.u., (b) photoelectric, (c) oxide, (d) space charge, (e) Child's, (f) Langmuir's.

CHAPTER 2

(a) currents, (b) True, (c) node, mesh, (d) impedance, (e) voltage, current, (f) Superposition.

CHAPTER 3

(a) positive, (b) apparent, (c) r.m.s., (d) natural, (e) minimum, (f) Q-factor, (g) inductance, (h) False.

CHAPTER 4

(a) False, (b) negative, (c) static, (d) large, (e) negative, (f) grid, (g) transconductance, (h) plate, (i) plate, power.

CHAPTER 5

(a) directly, (b) Einstein, (c) work function, (d) False, (e) threshold, (f) light, electrical, (g) semiconductor, (h) photoconductive.

CHAPTER 6

(a) electrostatically, (b) barium, strontium, (c) lower, (d) mm/volt, (e) milliampere, (f) anode, (g) saw-tooth.

CHAPTER 7

(a) D.C., (b) filter, (c) half-wave, (d) a.c., d.c., (e) d.c., a.c., (f) True, (g) opposite, (h) minimum.

CHAPTER 8

(a) radio, (b) False, (c) high, (d) phase, (e) True, (f) feedback, (g) independent, (h) power.

CHAPTER 9

(a) d.c., a.c., (b) amplitude, (c) 30, (d) feedback, (e) R.C., (f) cathode, anode, (g) False.

CHAPTER 10

(a) Modulation, (b) greater, (c) 90°, (d) carrier, lower, (e) twice, (f) detectors, (g) superheterodyne, (h) plate detection.

Chapter 11

(a) radio telephony, radio telegraphy, (b) vertically polarised, (c) 180°, (d) ionosphere, (e) False, (f) 10^5, (g) fidelity, (h) intermediate frequency.

Chapter 12

(a) scanning, (b) interlaced, (c) 30, (d) 25, (e) red, blue, green, (f) Radio, Detection, Ranging, (g) range, azimuth.

Chapter 13

(a) 10^{-6}, 10^3, (b) insulators, (c) *P*-type, (d) positive, negative, (e) Low, high, (f) reverse, (g) True, (h) False.

Chapter 14

(a) Bardeen, Brattain, (b) silicon, (c) emitter, base, collector, (d) emitter, (e) I_E, V_{EB}, (f) I_C, I_B, (g) impedance, admittance, hybrid, (h) base, (i) highest, (j) forward, reverse, (k) emitter, base, collector.

Chapter 15

(a) Collector, (b) I_D, V_{DS}, V_{GS}, (c) P, (d) gate, (e) stabilized, (f) constant, (g) is not, (h) positively, (i) enhancement, (j) is, (k) high.

Chapter 16

(a) Silicon, (b) transistors, diodes, (c) resistors, capacitors, (d) false, (e) linear, digital, (f) TO-5, flatpack, dual-in-line, (g) linear, (h) computers, calculators, (i) false, (j) ICs, (k) UP, (l) DOWN, (m) One; UP, (n) two; AND, (o) OR, (p) two; OR, (q) present, (r) NAND, (s) AND, (t) NOR, (u) true, (v) 1110, (w) 10100, (x) 11, (y) 27, (z) 11000100.

Chapter 17

(a) False, (b) commercial, (c) zero, (d) $1+\dfrac{R_f}{R}$, (e) low, (f) capacitor, (g) difference.

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